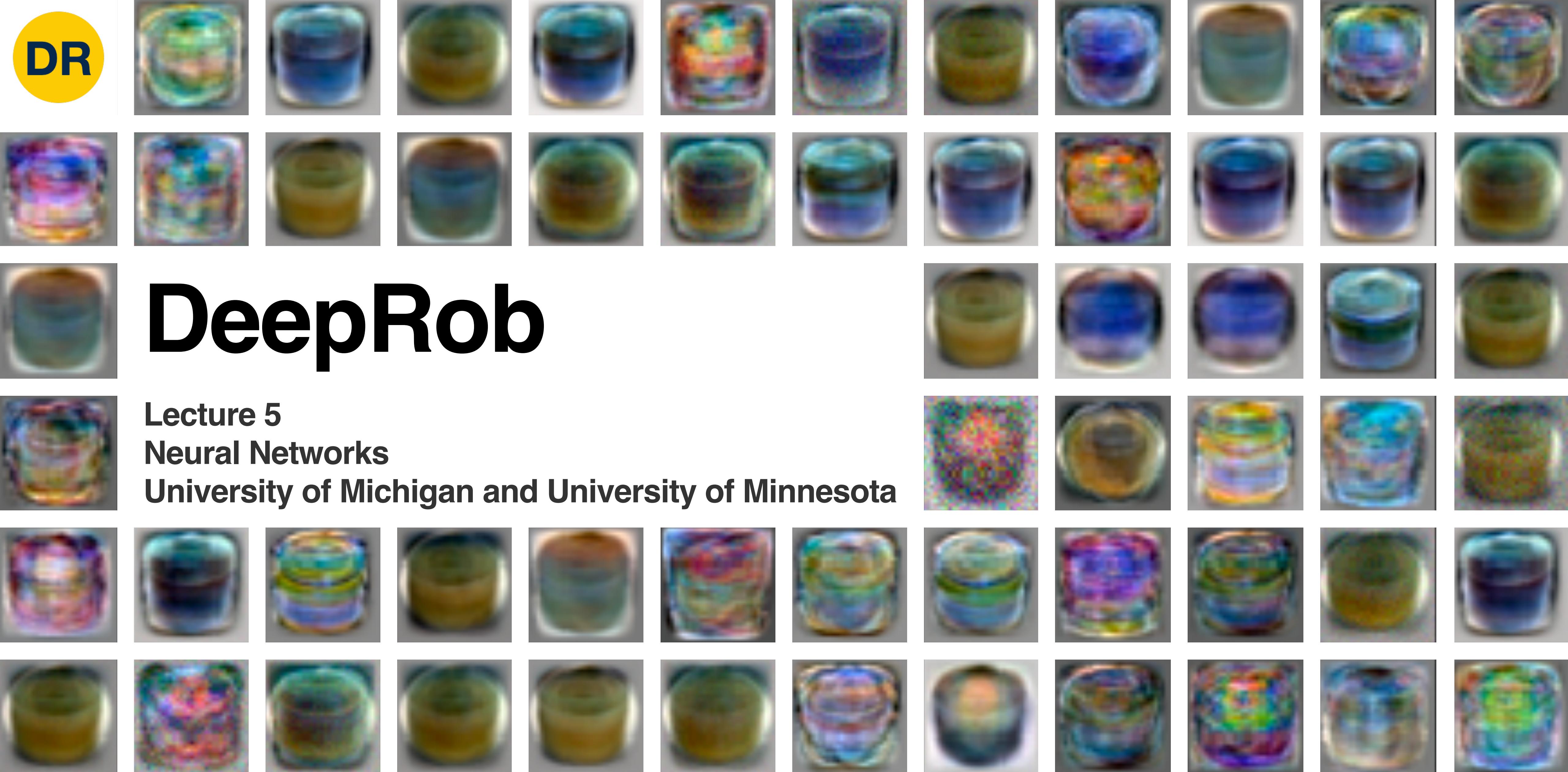


**DR**



# DeepRob

**Lecture 5**  
**Neural Networks**  
**University of Michigan and University of Minnesota**

# Project 1 – Reminder

---

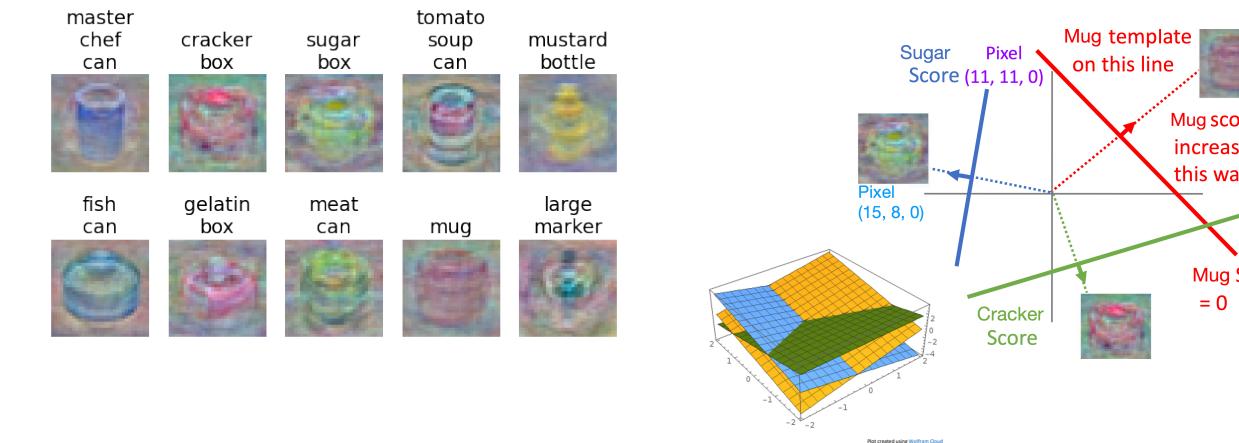
- Instructions and code available on the website
  - Here: [deeprob.org/projects/project1/](https://deeprob.org/projects/project1/)
- Uses Python, PyTorch and Google Colab
- Implement KNN, linear SVM, and linear softmax classifiers
- **Autograder is online and updated**
- **Due Thursday, January 26th 11:59 PM EST**



# Recap from Previous Lectures

- Use **Linear Models** for image classification problems.
- Use **Loss Functions** to express preferences over different choices of weights.
- Use **Regularization** to prevent overfitting to training data.
- Use **Stochastic Gradient Descent** to minimize our loss functions and train the model.

$$s = f(x; W) = Wx$$



$$L_i = -\log\left(\frac{\exp^{s_{y_i}}}{\sum_j \exp^{s_j}}\right)$$

**Softmax**

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

**SVM**

$$L = \frac{1}{N} \sum_{i=1}^N L_i + R(W)$$

```
v = 0
for t in range(num_steps):
    dw = compute_gradient(w)
    v = rho * v + dw
    w -= learning_rate * v
```



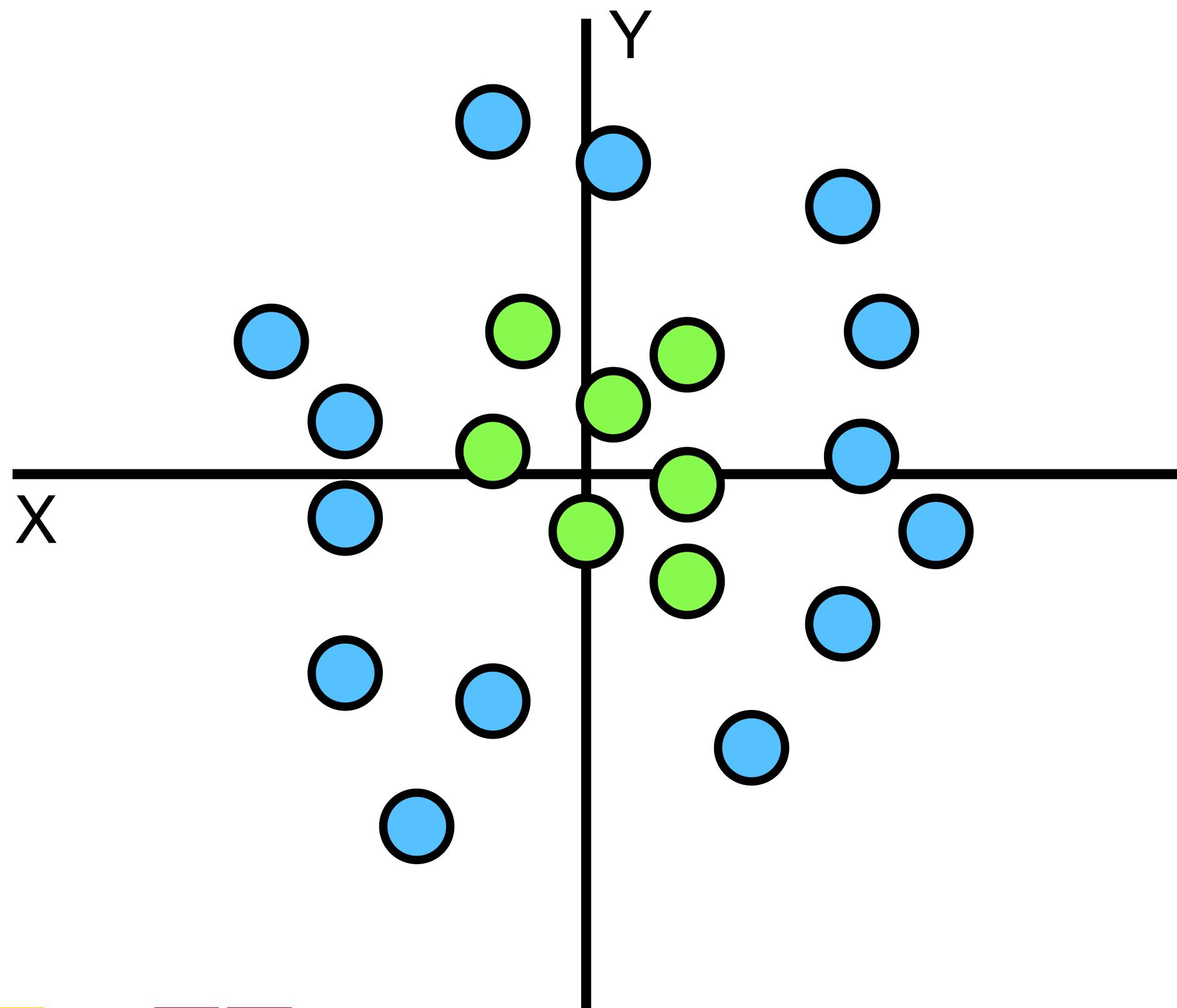


# Neural Networks



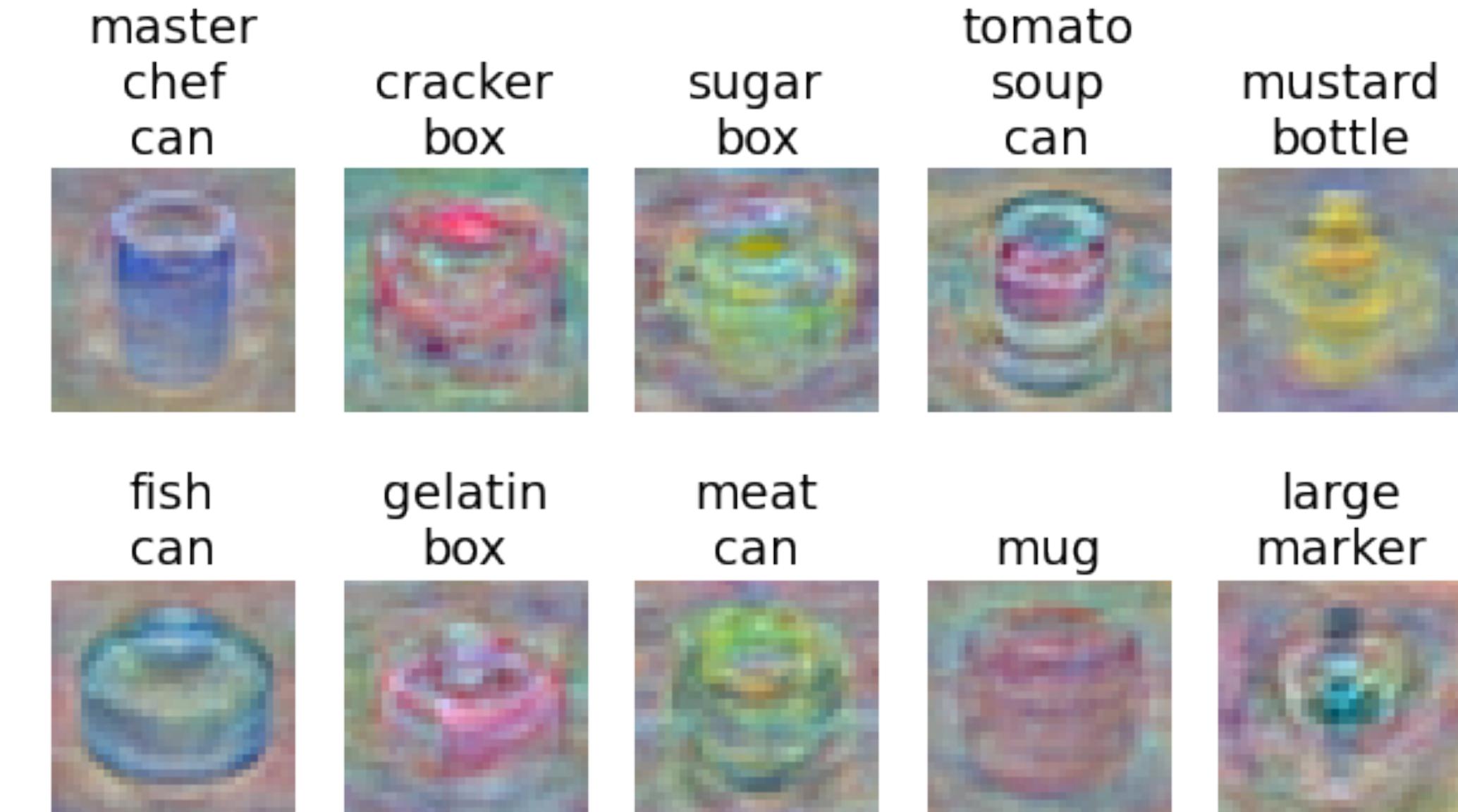
# Problem: Linear Classifiers aren't that powerful

## Geometric Viewpoint



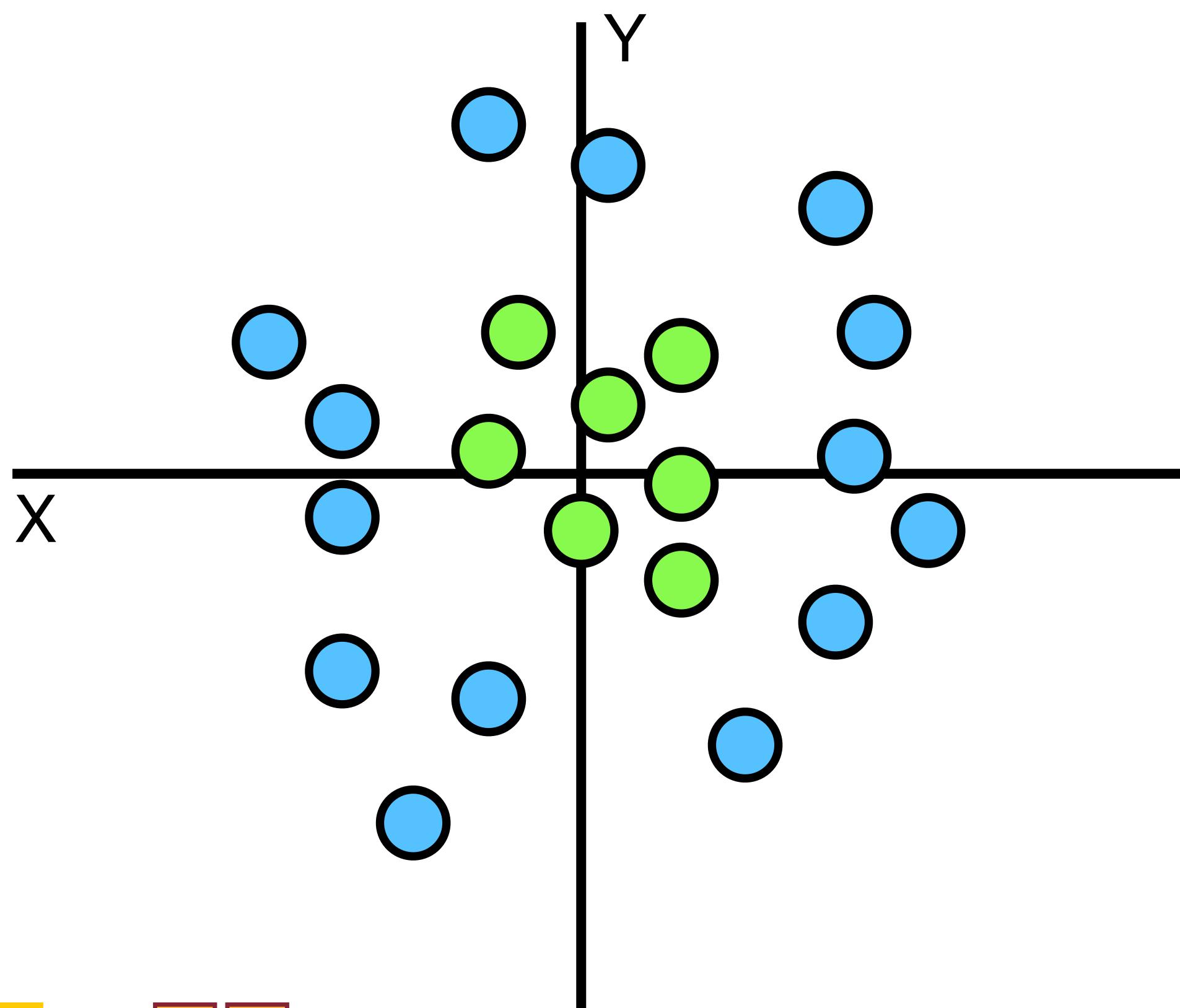
## Visual Viewpoint

One template per class:  
Can't recognize different modes of a  
class



# One solution: Feature Transforms

Original space

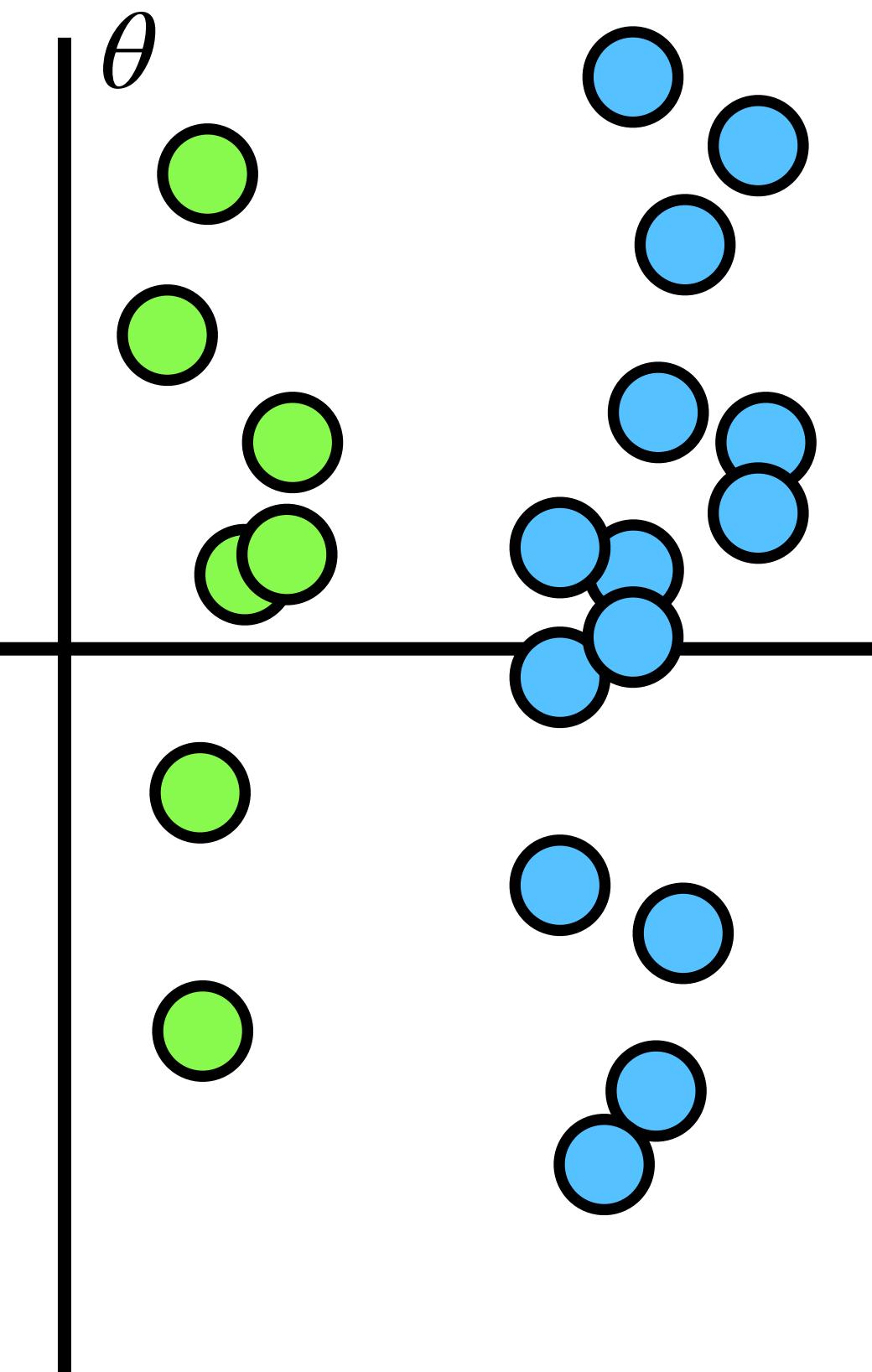


$$r = (x^2 + y^2)^{1/2}$$

$$\theta = \tan^{-1}(y/x)$$

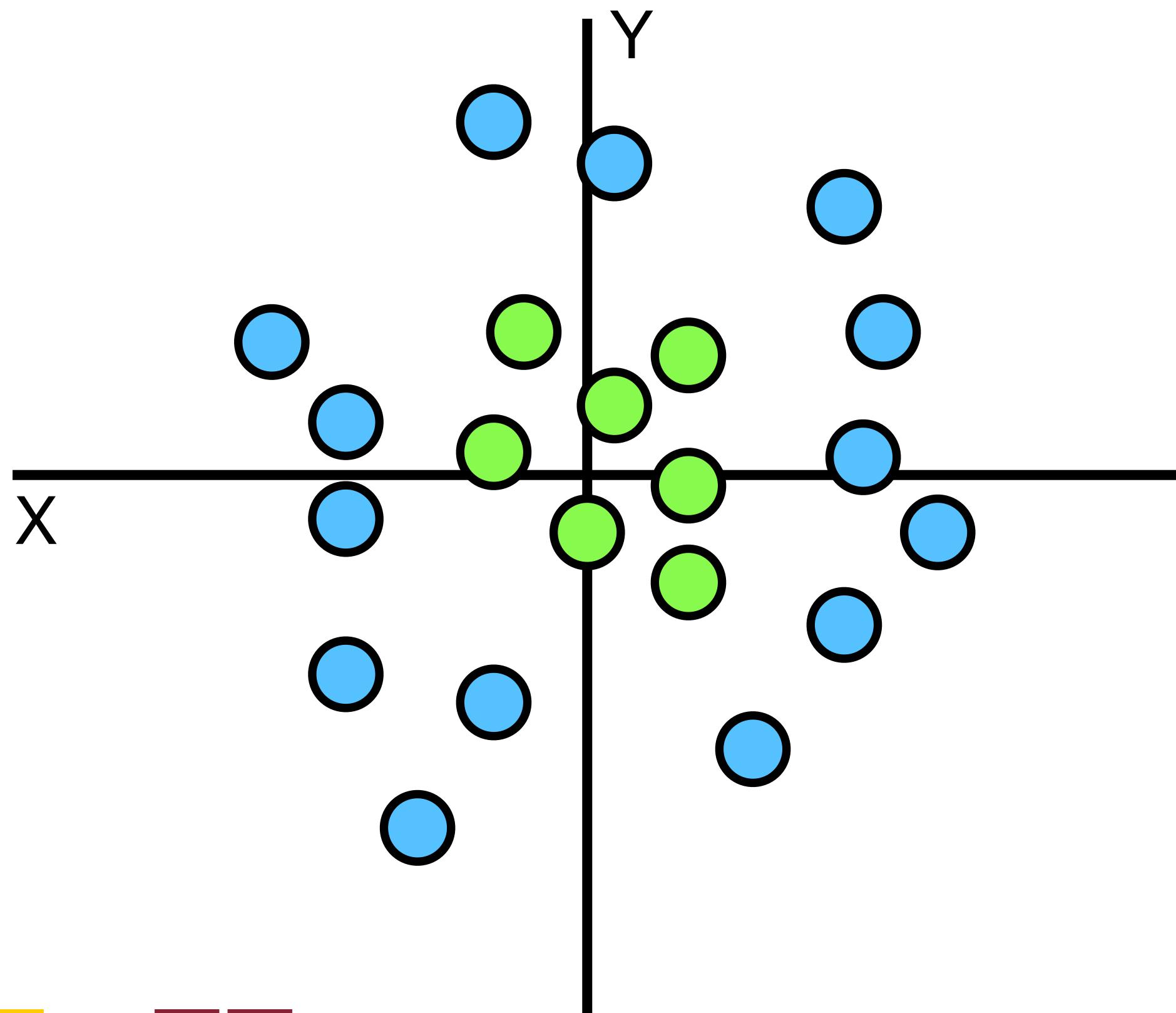
Feature  
Transform

Feature space



# One solution: Feature Transforms

Original space

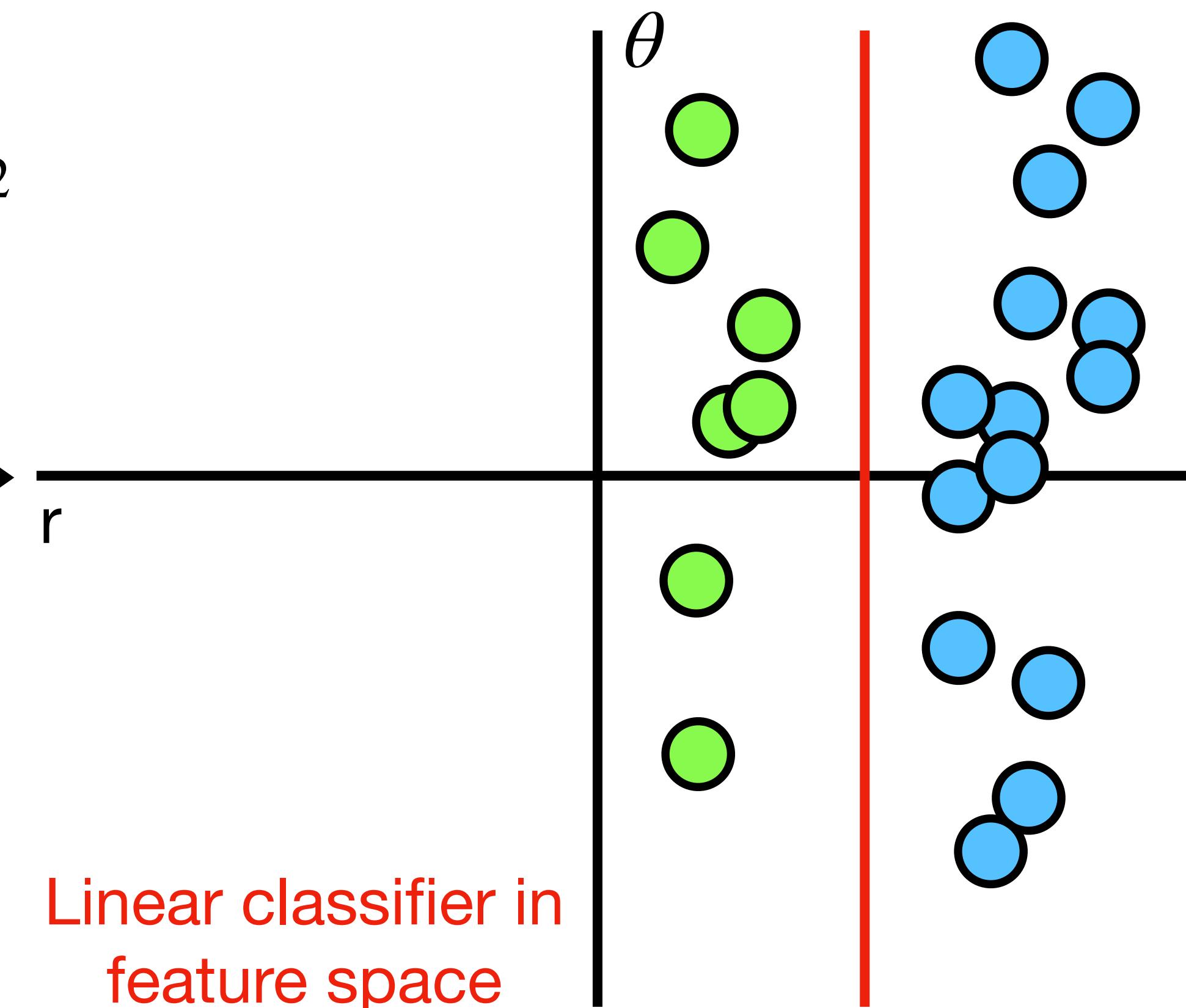


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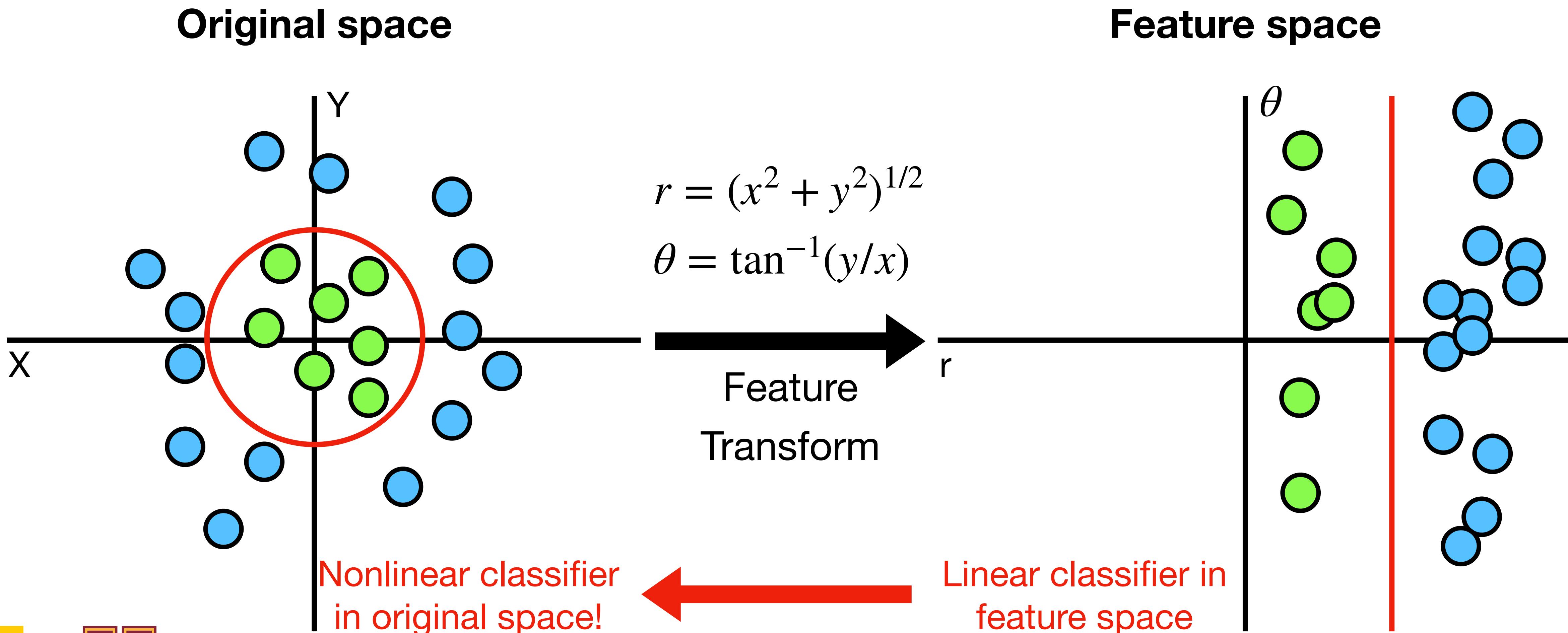
Feature  
Transform

Feature space

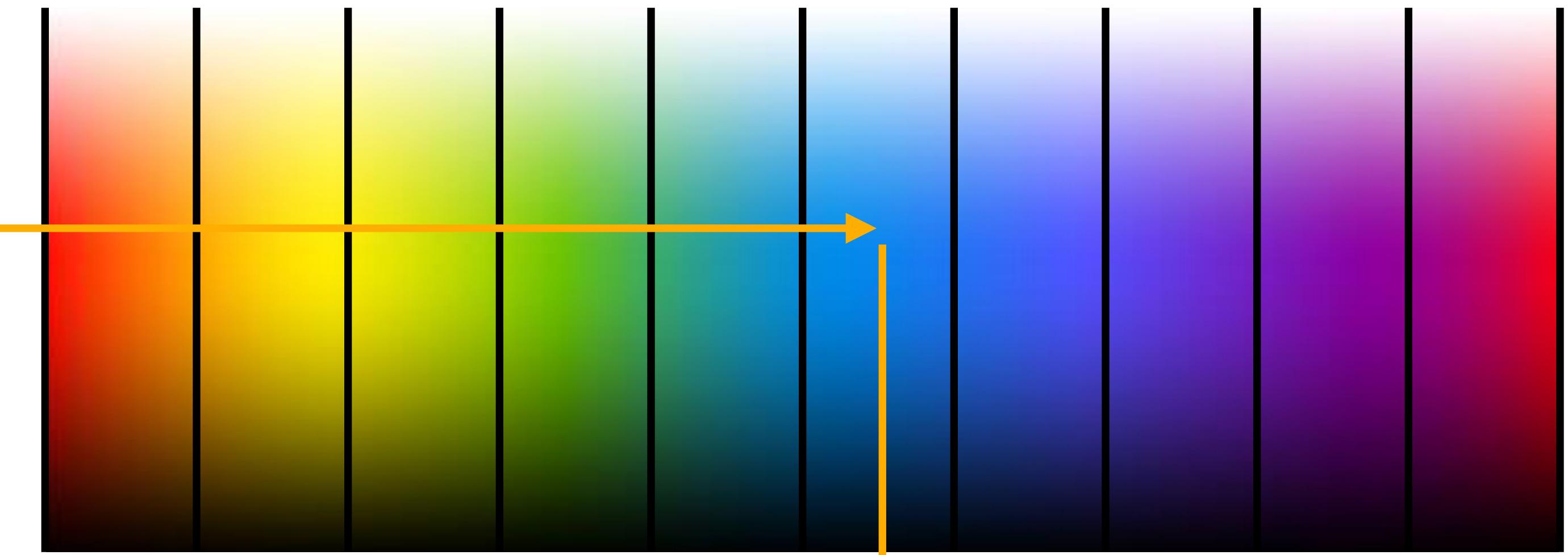


Linear classifier in  
feature space

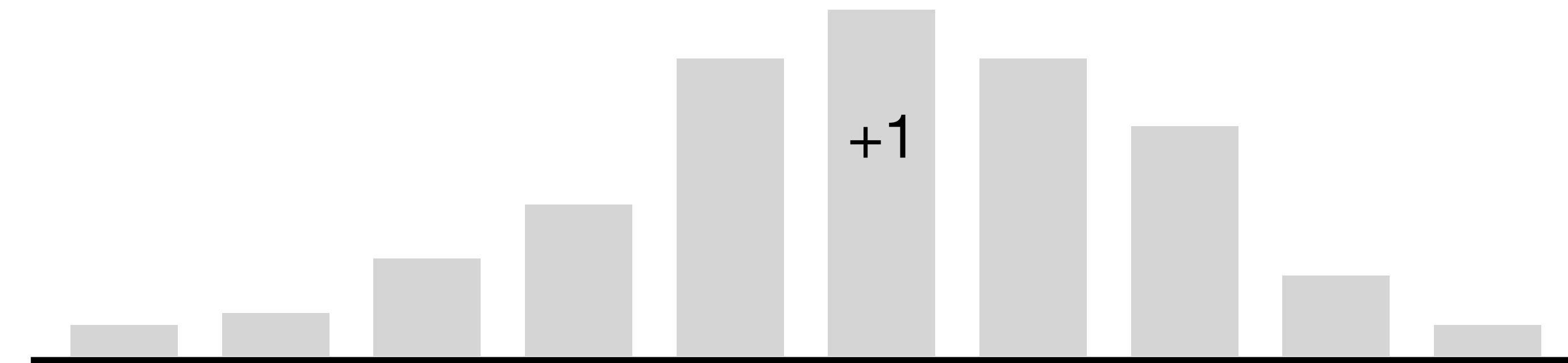
# One solution: Feature Transforms



# Image Features: Color Histogram



Ignores texture,  
spatial positions



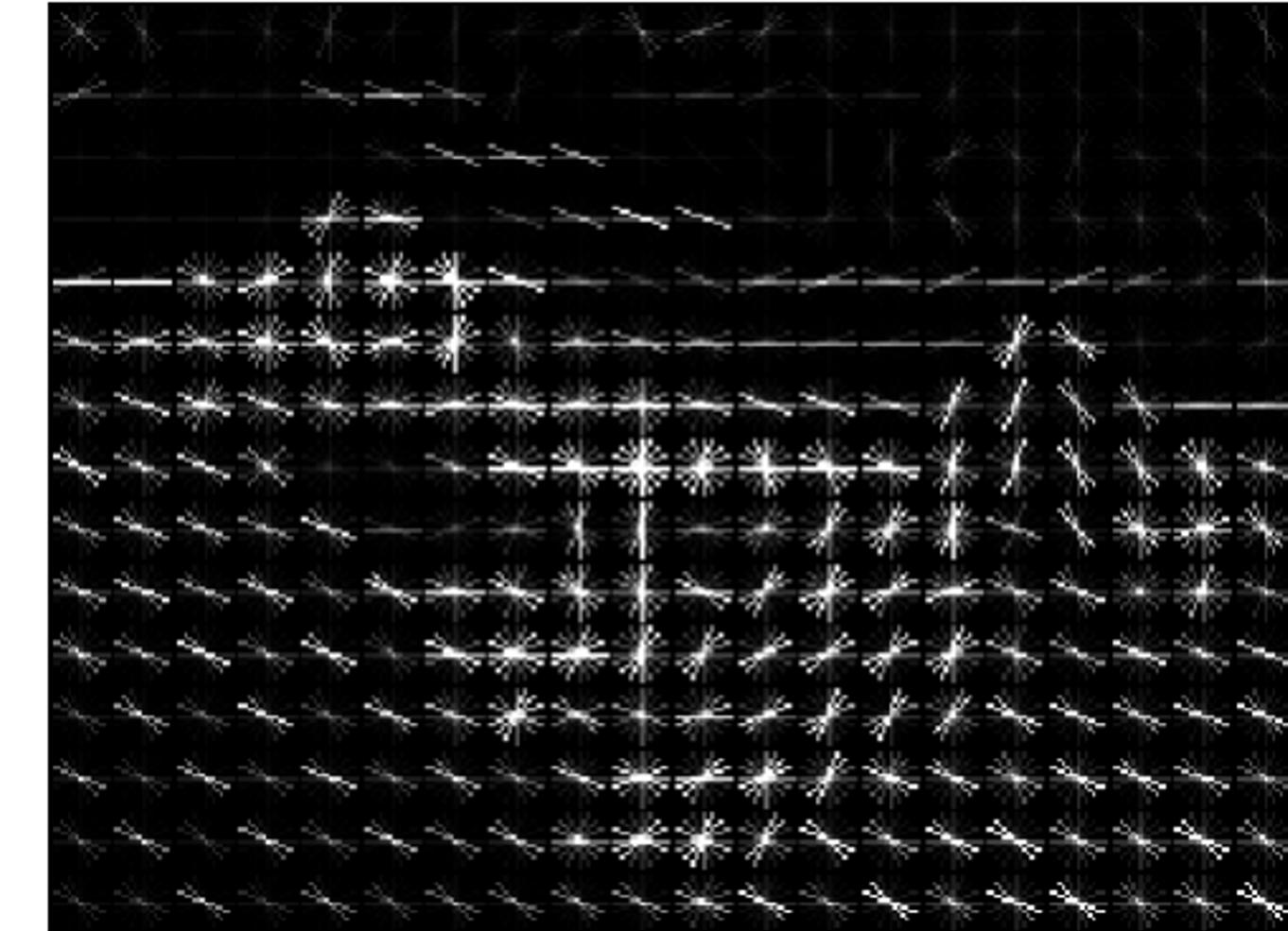
[Frog image](#) is in the public domain

# Image Features: Histogram of Oriented Gradients (HoG)



1. Compute edge direction/  
strength at each pixel
2. Divide image into 8x8 regions
3. Within each region compute a  
histogram of edge direction  
weighted by edge strength

# Image Features: Histogram of Oriented Gradients (HoG)



1. Compute edge direction/strength at each pixel
2. Divide image into 8x8 regions
3. Within each region compute a histogram of edge direction weighted by edge strength

Example: 320x240 image gets divided into 40x30 bins; 9 directions per bin; feature vector has  $30 \times 40 \times 9 = 10,800$  numbers

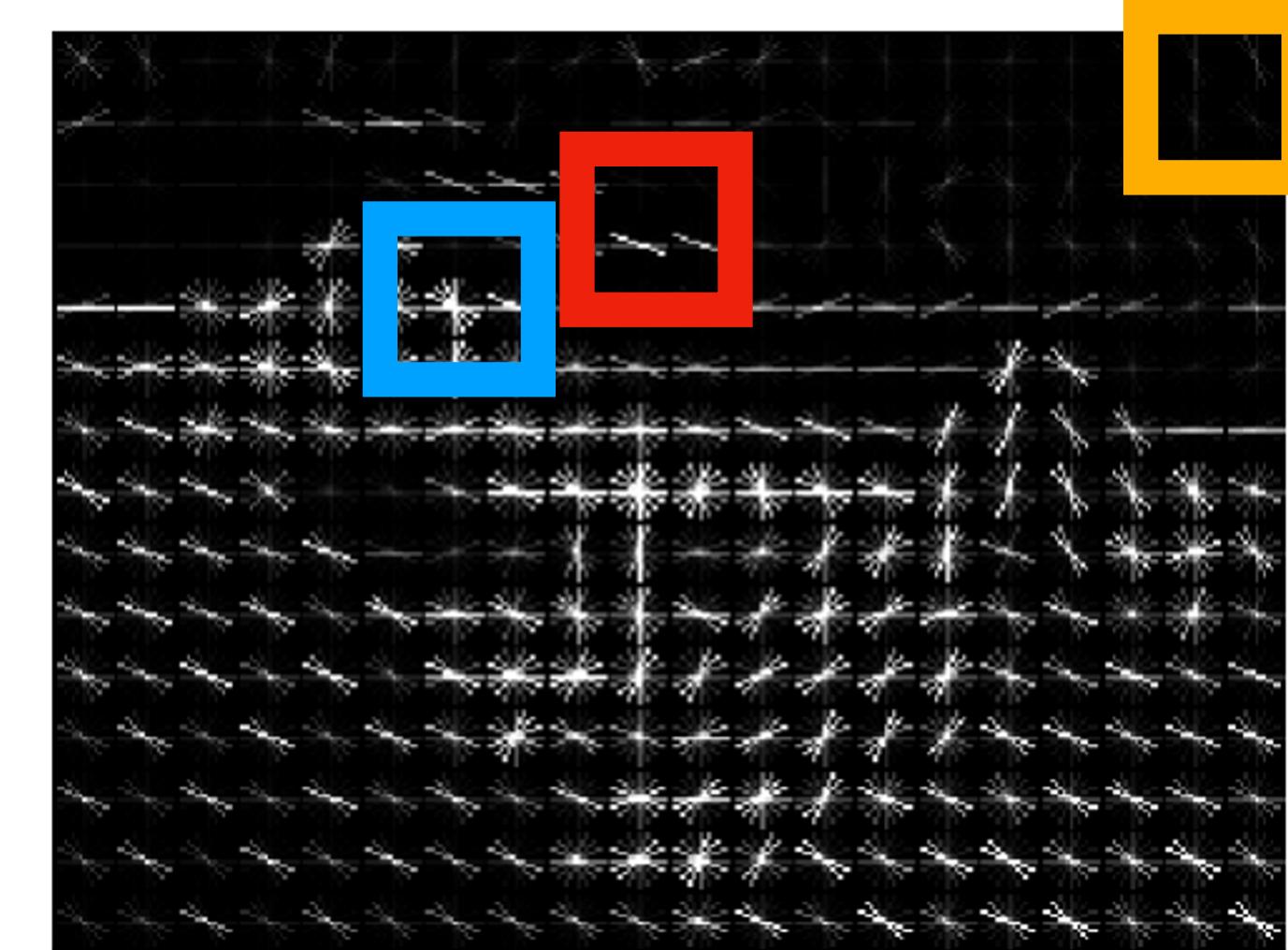
# Image Features: Histogram of Oriented Gradients (HoG)



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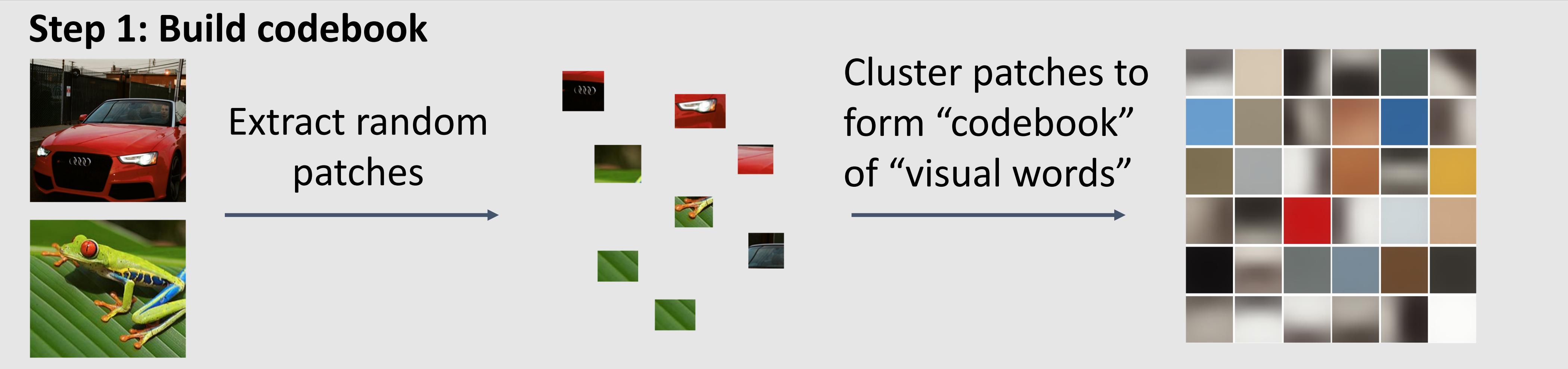
Weak edges  
Strong diagonal edges  
→  
Edges in all directions

Capture texture and position, robust to small image changes

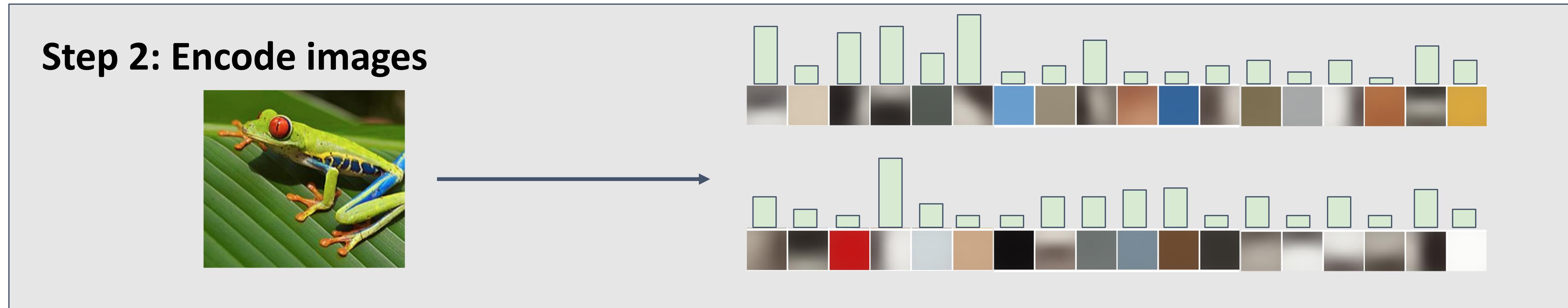
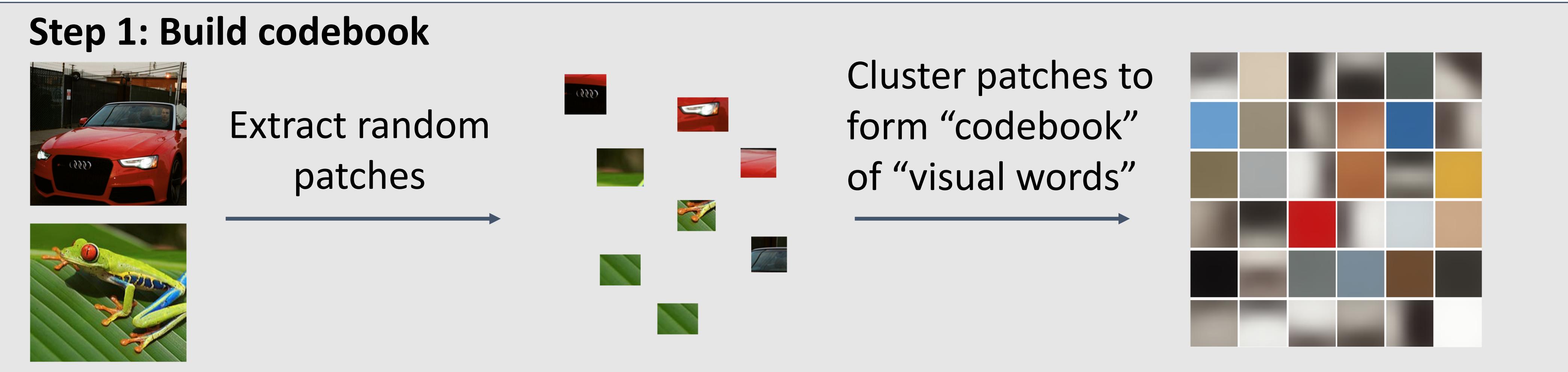


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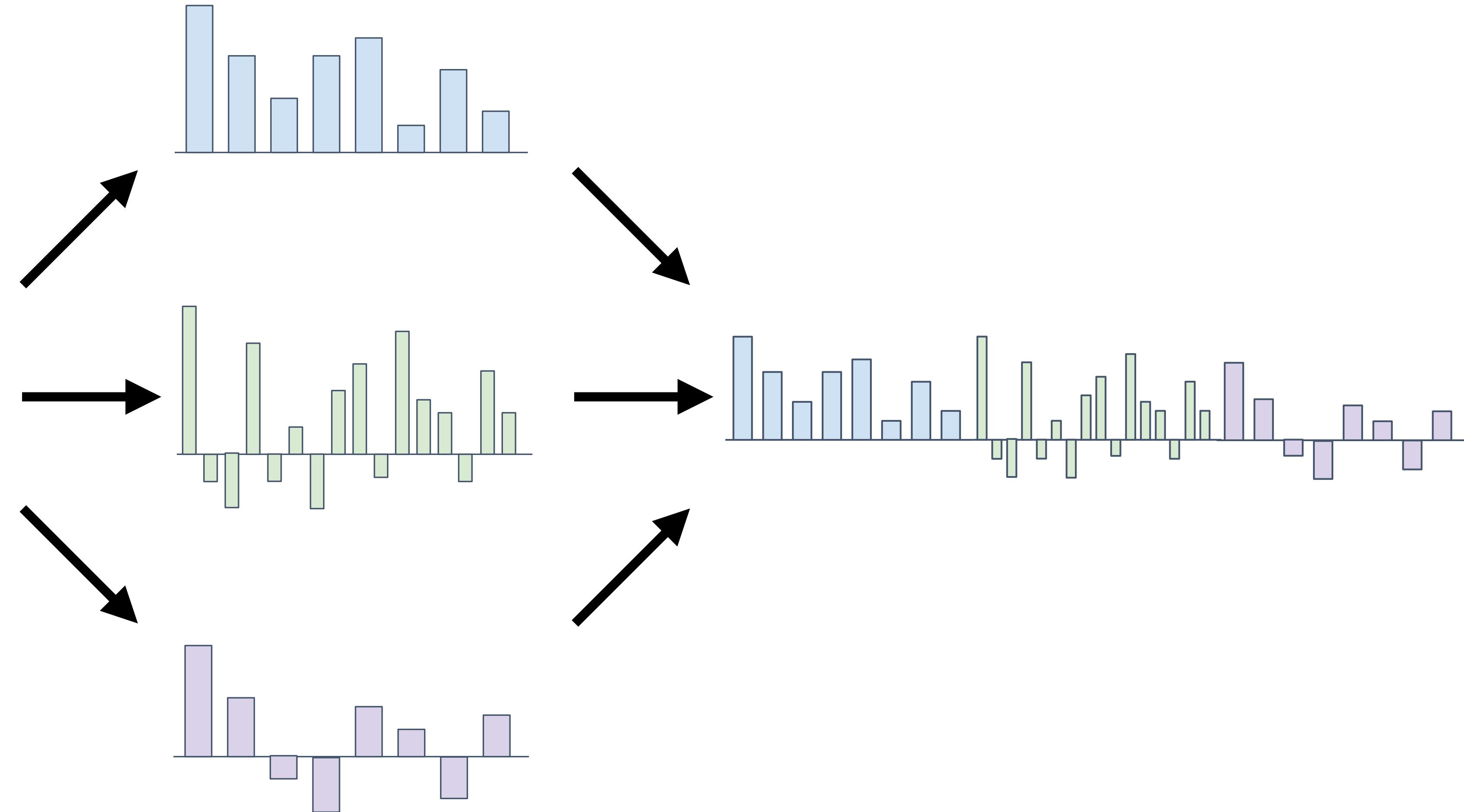
# Image Features: Bag of Words (Data-Driven!)



# Image Features: Bag of Words (Data-Driven!)



# Image Features



# Example: Winner of 2011 ImageNet Challenge

---

Low-level feature extraction  $\approx$  10k patches per image

- SIFT: 128-dims
  - Color: 96-dim
- } Reduced to 64-dim with PCA

FV extraction and compression:

- $N=1024$  Gaussians,  $R=4$  regions  $\rightarrow$  520K dim x 2
- Compression:  $G=8$ ,  $b=1$  bit per dimension

One-vs-all SVM learning with SGD

Late fusion of SIFT and color systems



# Image Features vs Neural Networks



$f$

←

training

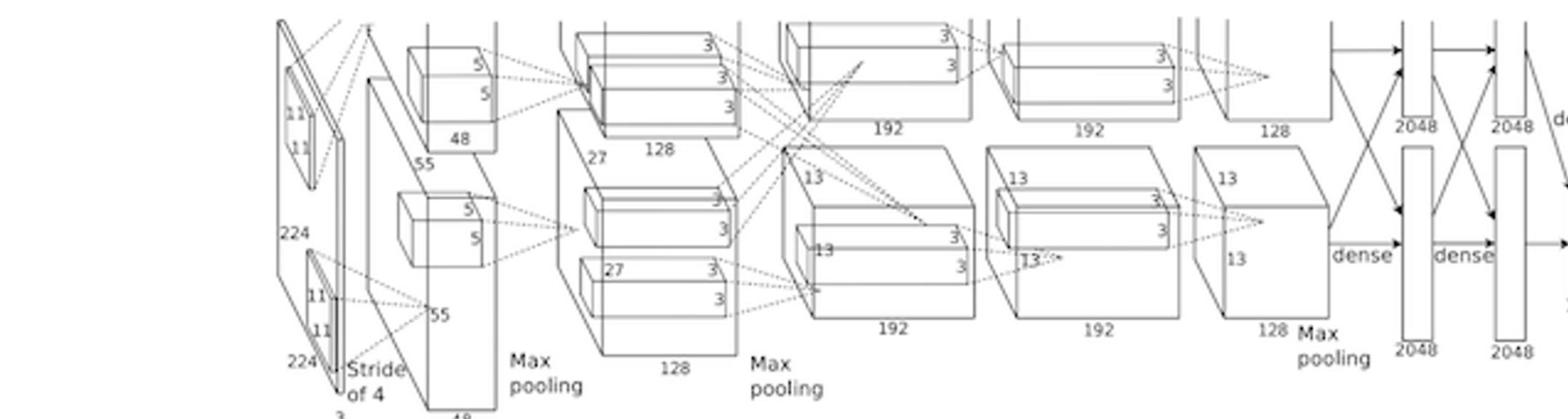
10 numbers giving  
scores for classes

# Image Features vs Neural Networks



$f$  →  
← training

10 numbers giving scores for classes



Krizhevsky, Sutskever, and Hinton, "Imagenet classification with deep convolutional neural networks", NIPS 2012.  
Figure copyright Krizhevsky, Sutskever, and Hinton, 2012.  
Reproduced with permission.

← training

10 numbers giving scores for classes

# Neural Networks

---

**Input:**  $x \in \mathbb{R}^D$

**Output:**  $f(x) \in \mathbb{R}^C$

**Before:** Linear Classifier:  $f(x) = Wx + b$

Learnable parameters:  $W \in \mathbb{R}^{D \times C}, b \in \mathbb{R}^C$



# Neural Networks

---

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Feature Extraction

Linear Classifier

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Or Three-Layer Neural Network:

$$f(x) = W_3 \max(0, W_2 \max(0, W_1 x + b_1) + b_2) + b_3$$

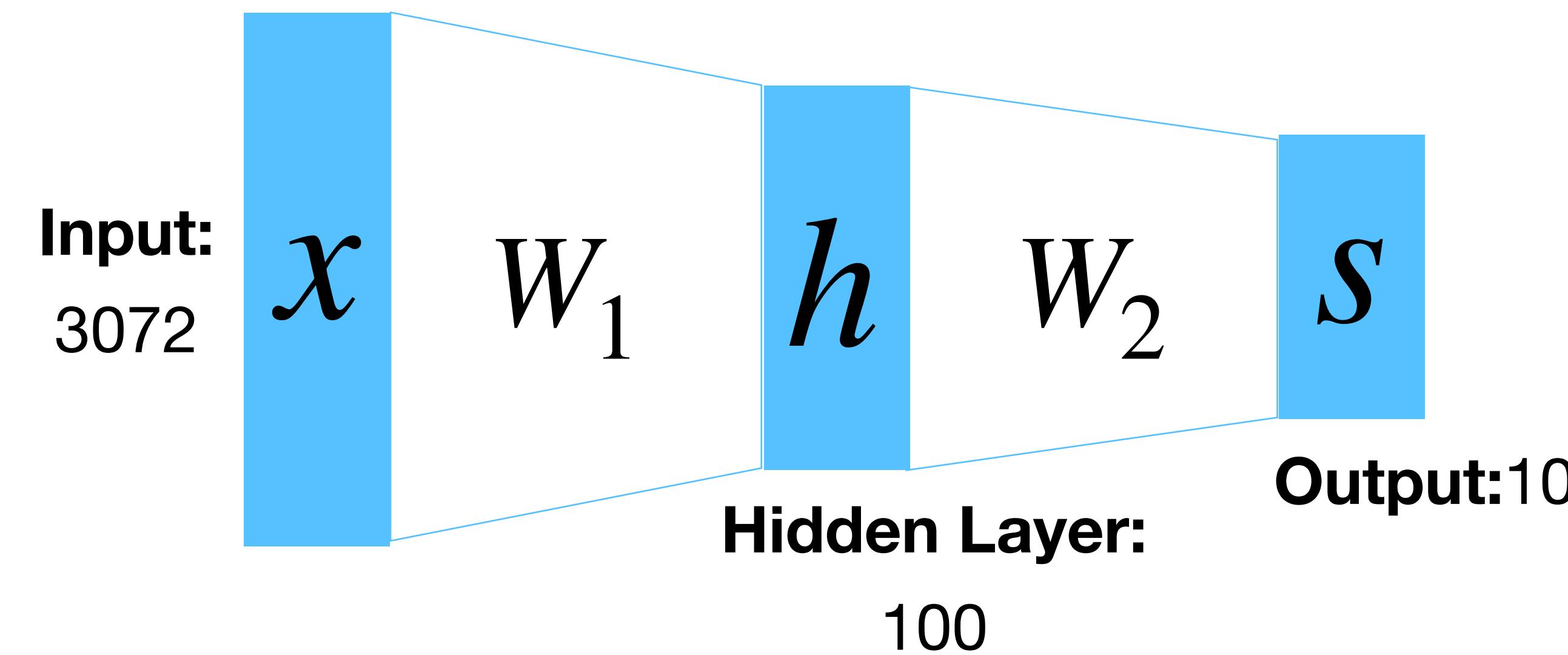

# Neural Networks

**Before:** Linear Classifier:

$$f(x) = Wx + b$$

**Now:** Two-Layer Neural Network:

$$f(x) = W_2 \max(0, W_1 x + b_1) + b_2$$



$$x \in \mathbb{R}^D, W_1 \in \mathbb{R}^{H \times D}, W_2 \in \mathbb{R}^{C \times H}$$



# Neural Networks

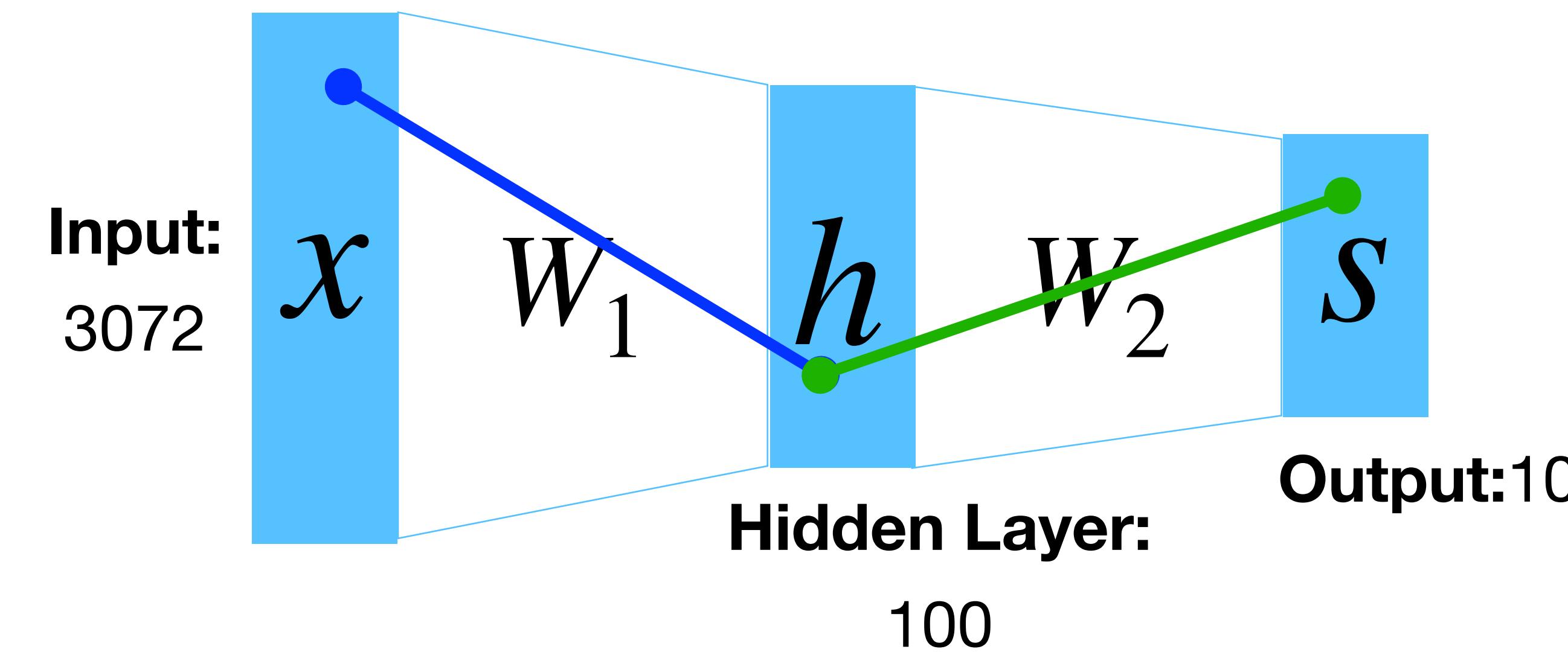
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$$f(x) = W_2 \max(0, W_1 x + b_1) + b_2$$

Element  $(i, j)$  of  $W_1$  gives the effect on  $h_i$  from  $x_j$



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# Neural Networks

**Before:** Linear Classifier:

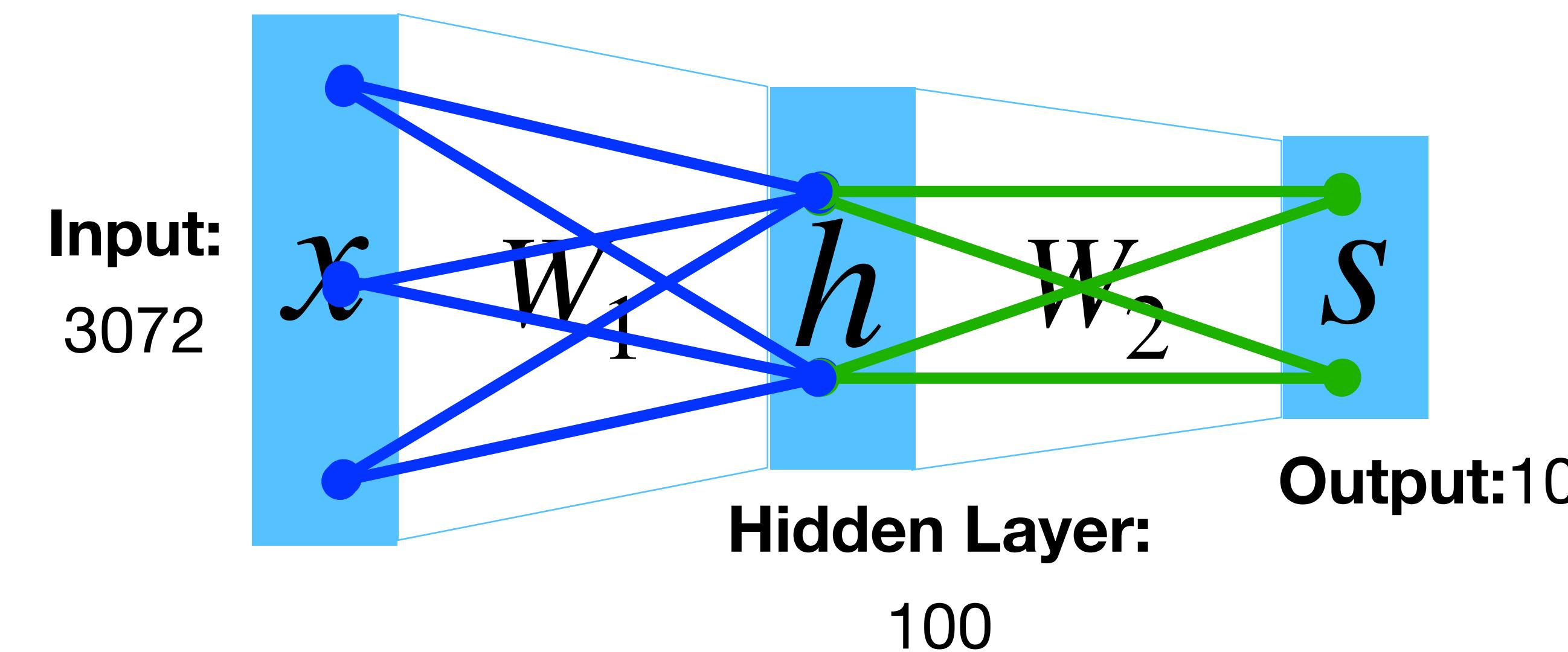
$$f(x) = Wx + b$$

**Now:** Two-Layer Neural Network:

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Element  $(i, j)$  of  $W_1$  gives the effect on  $h_i$  from  $x_j$

All elements of  $x$  affect all elements of  $h$



Element  $(i, j)$  of  $W_2$  gives the effect on  $s_i$  from  $h_j$

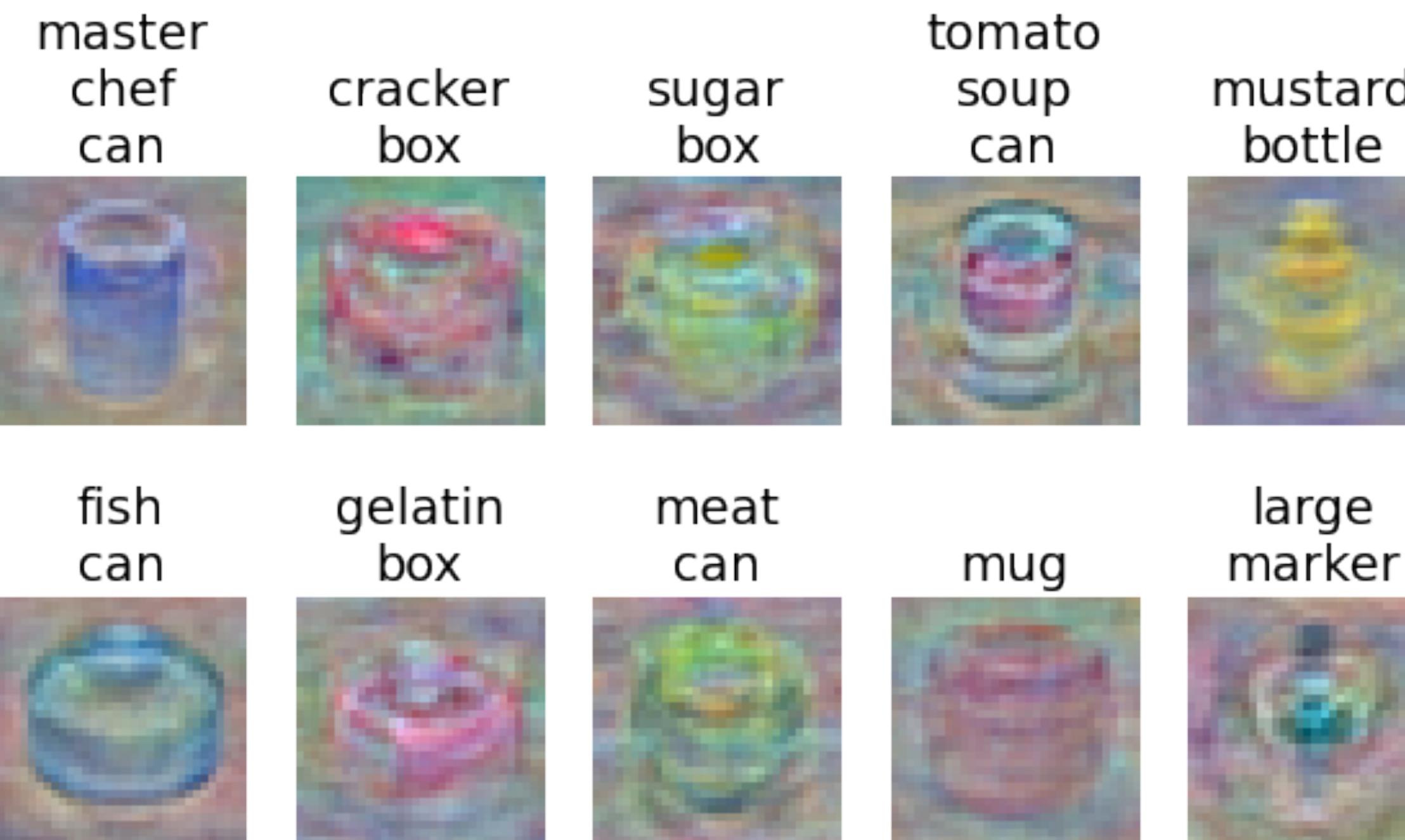
All elements of  $h$  affect all elements of  $s$

Fully-connected neural network also  
“Multi-Layer Perceptron” (MLP)

# Neural Networks

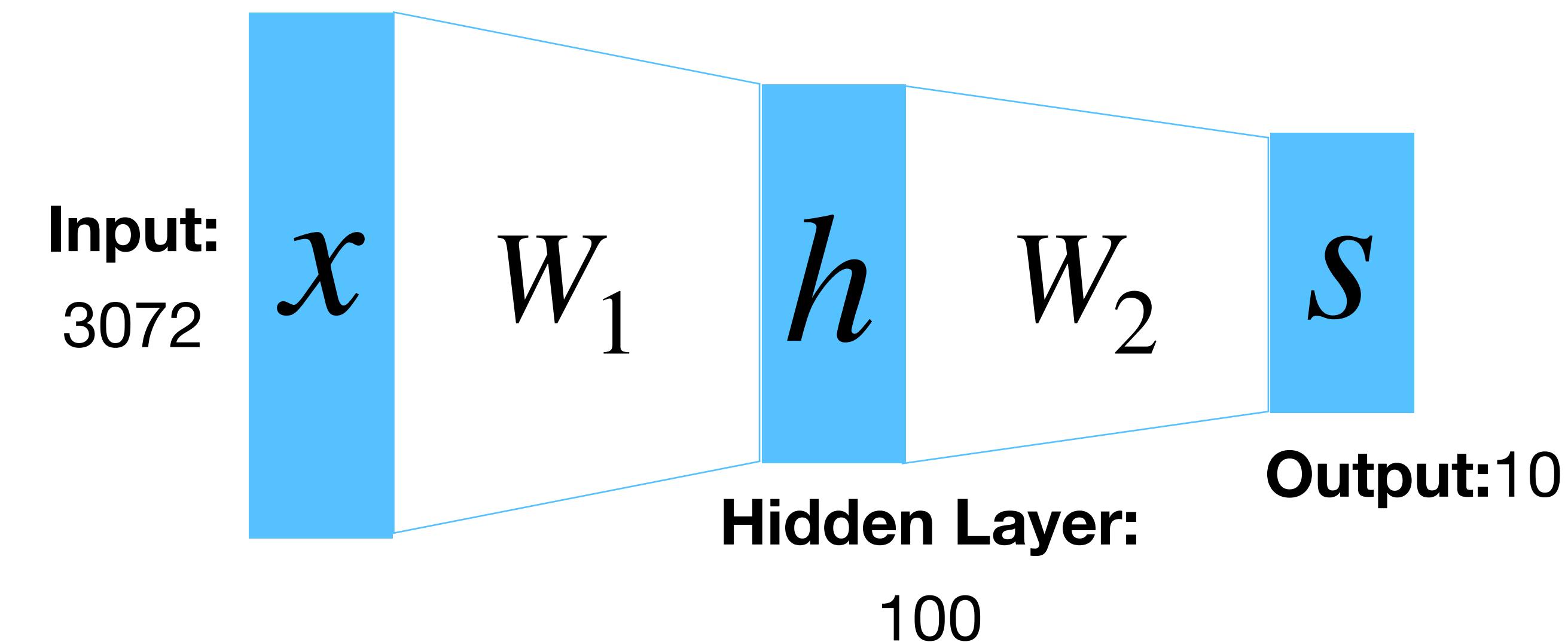
---

Linear classifier: One template per class



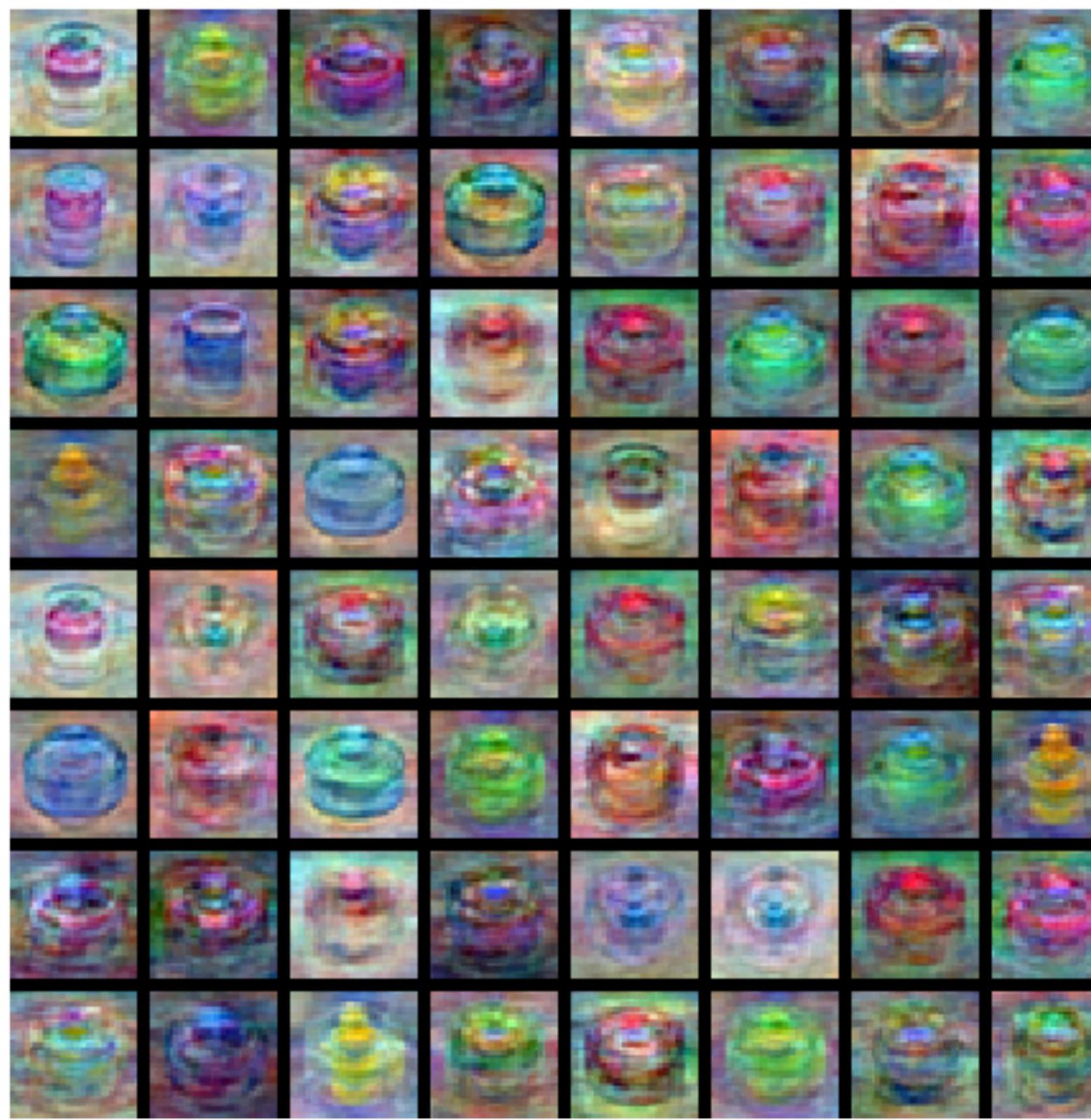
**Before:** Linear score function

**Now:** Two-Layer Neural Network:



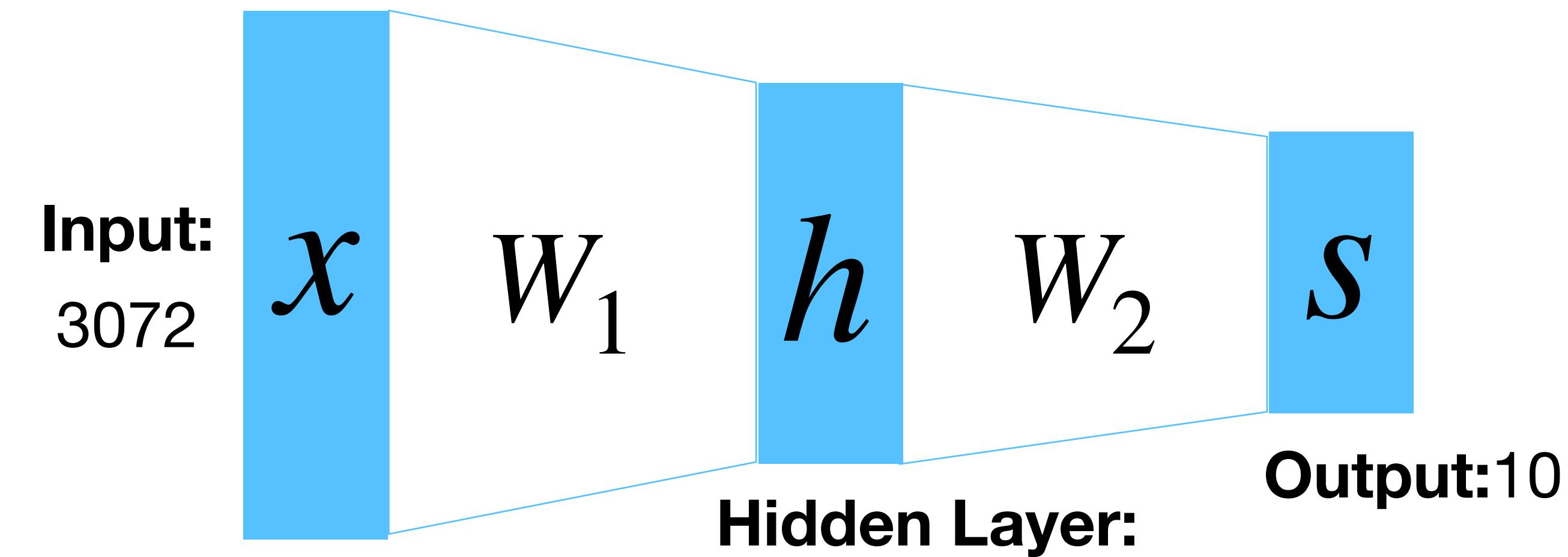
# Neural Networks

Neural net: first layer is bank of templates;  
Second layer recombines templates



**Before:** Linear score function

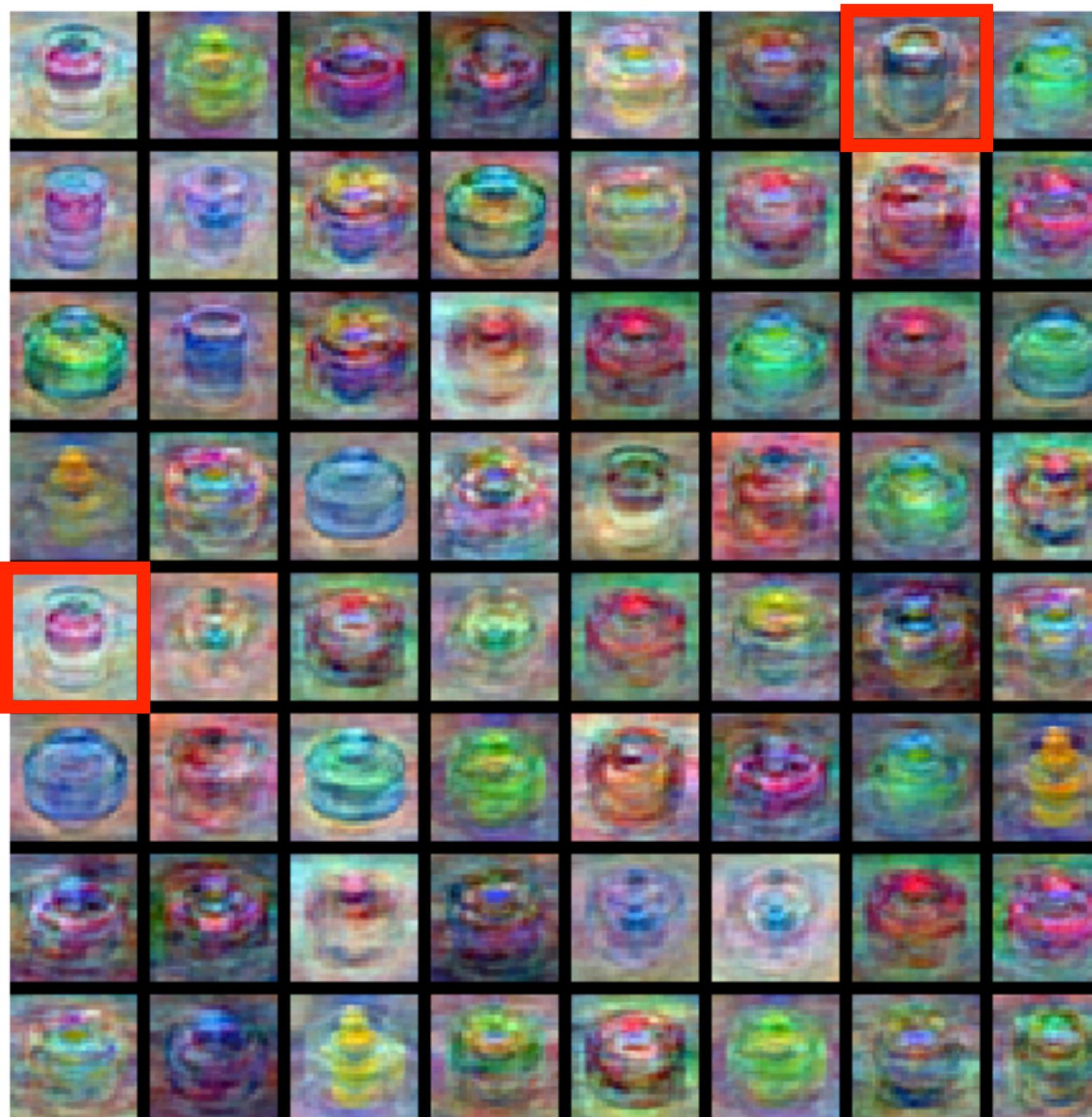
**Now:** Two-Layer Neural Network:



$$x \in \mathbb{R}^D, W_1 \in \mathbb{R}^{H \times D}, W_2 \in \mathbb{R}^{C \times H}$$

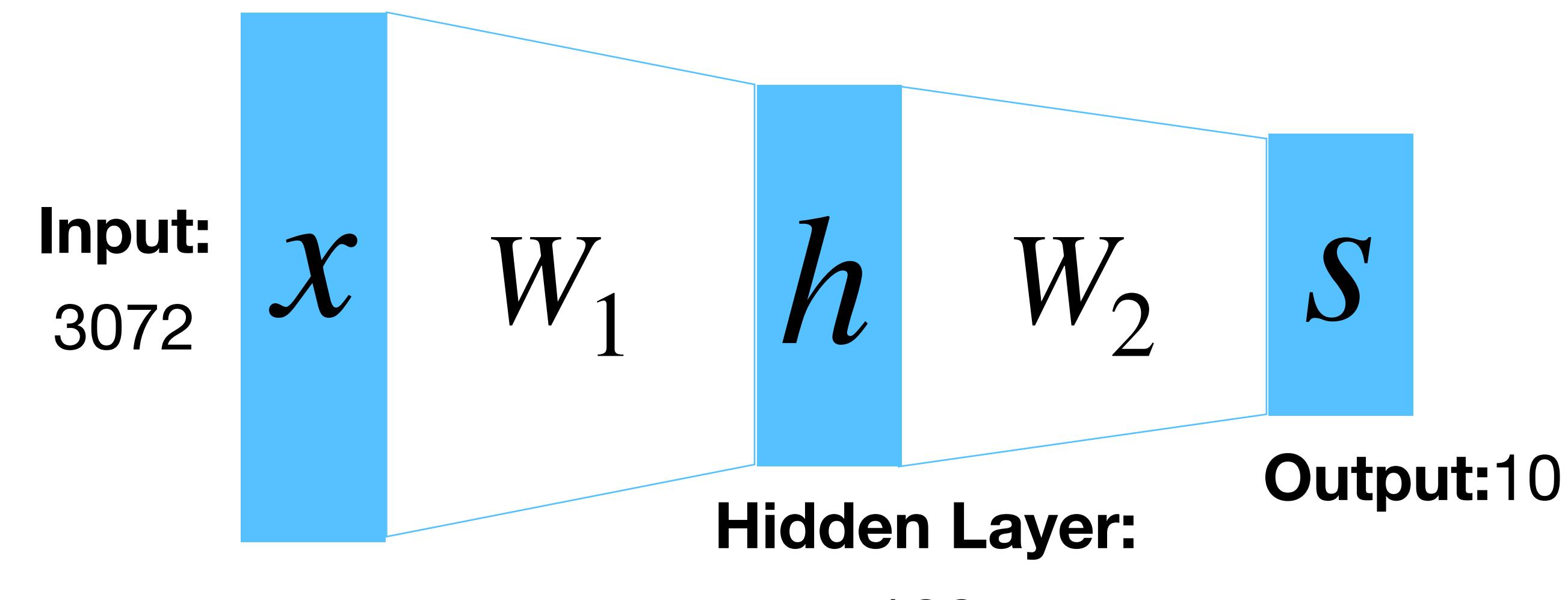
# Neural Networks

Can use different templates to cover multiple modes of a class!



**Before:** Linear score function

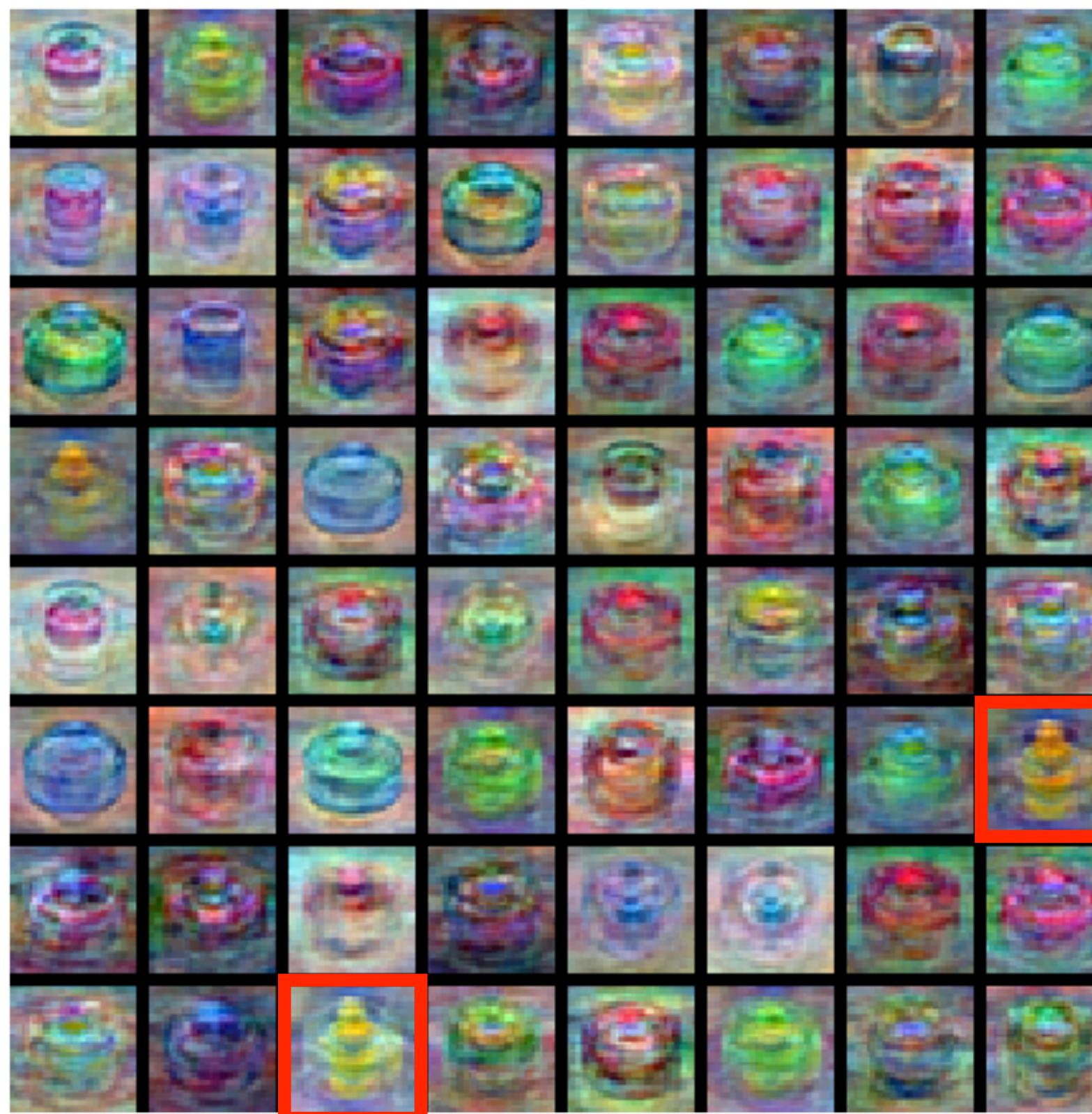
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$$x \in \mathbb{R}^D, W_1 \in \mathbb{R}^{H \times D}, W_2 \in \mathbb{R}^{C \times H}$$

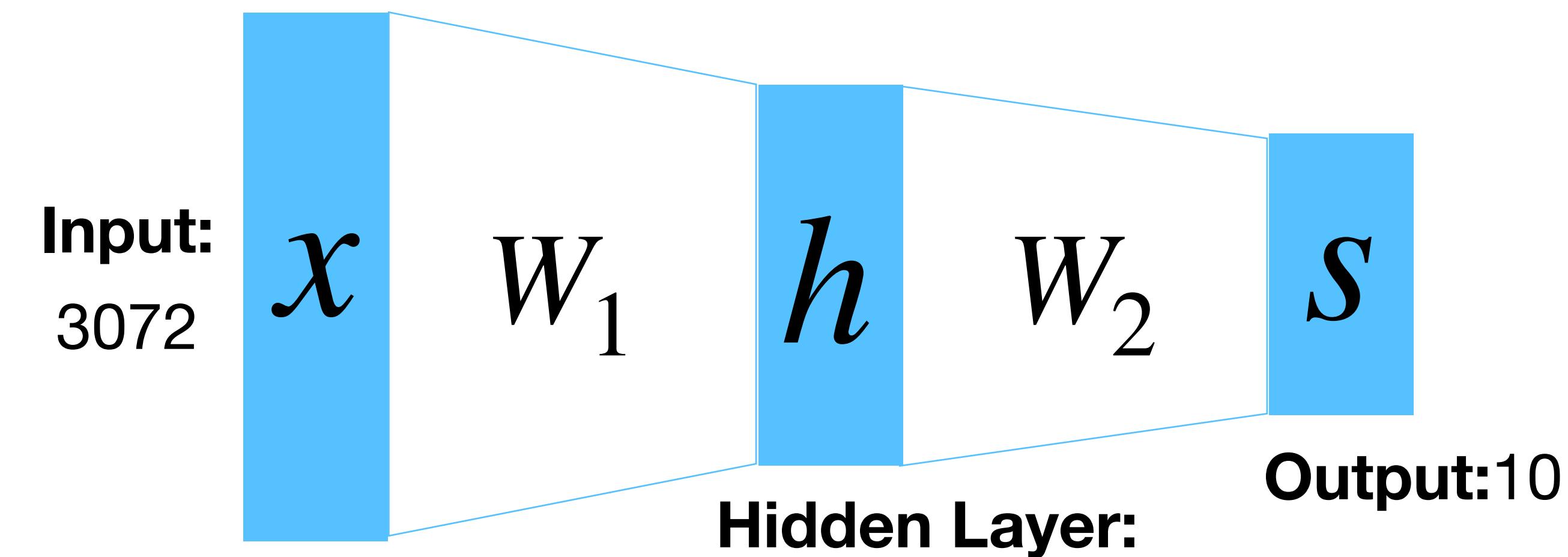
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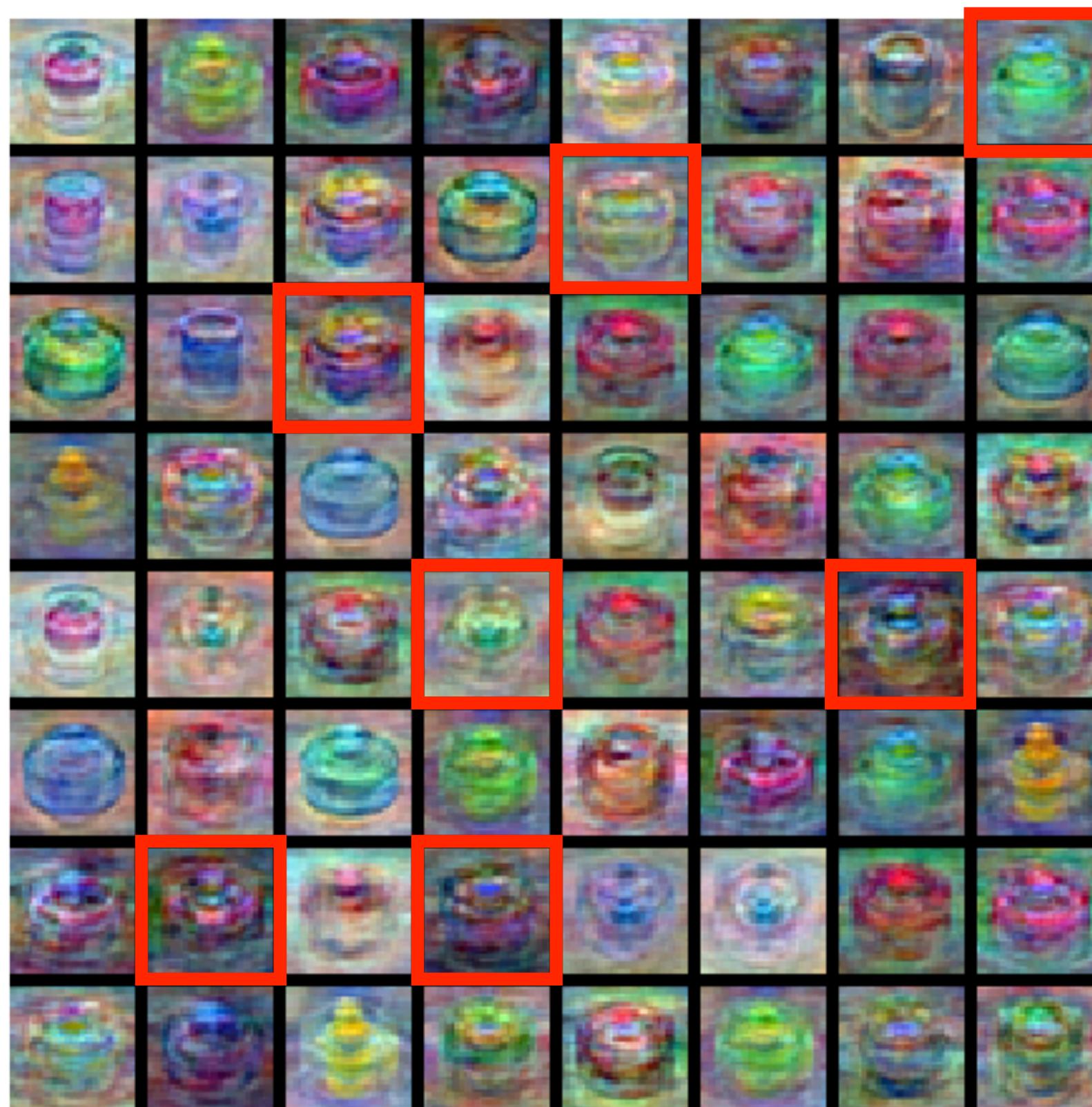
**Before:** Linear score function

**Now:** Two-Layer Neural Network:



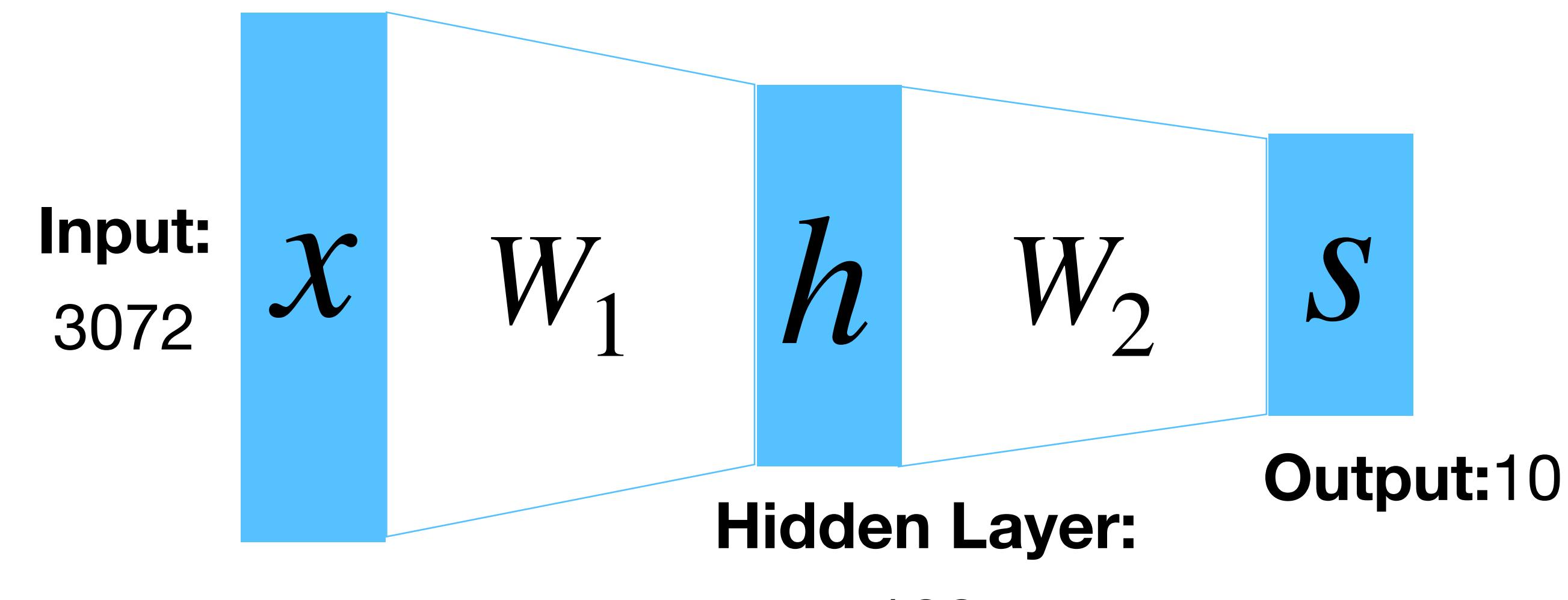
# Neural Networks

“Distributed representation”: Most templates not interpretable!



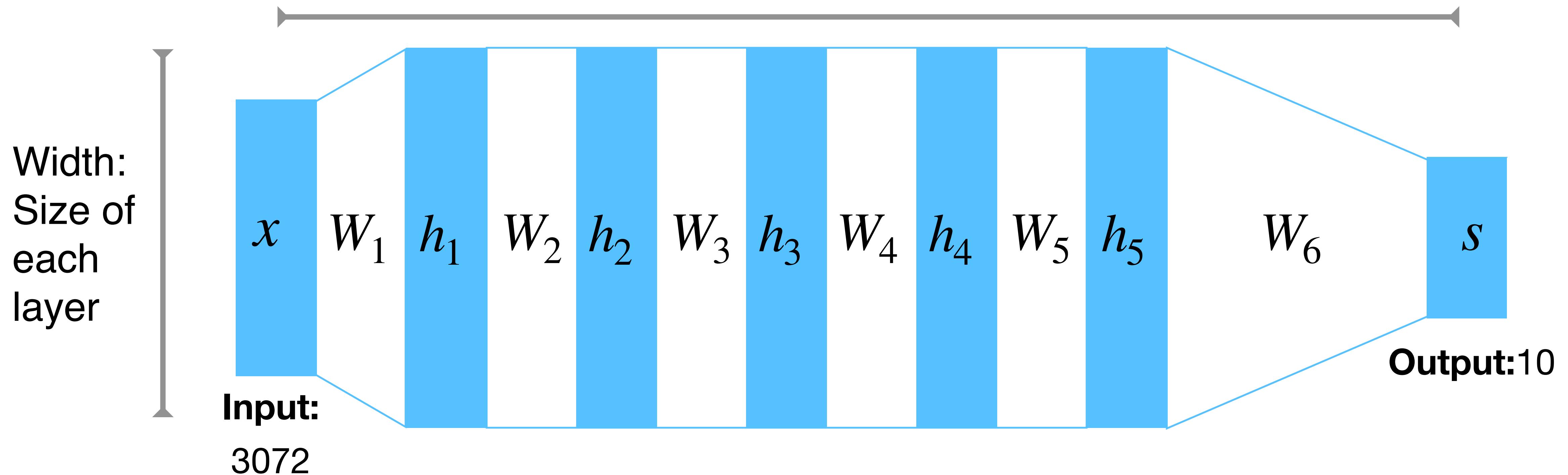
**Before:** Linear score function

**Now:** Two-Layer Neural Network:



# Deep Neural Networks

Depth = number of layers



$$s = W_6 \max(0, W_5 \max(0, W_4 \max(0, W_3 \max(0, W_2 \max(0, W_1 x)))))$$

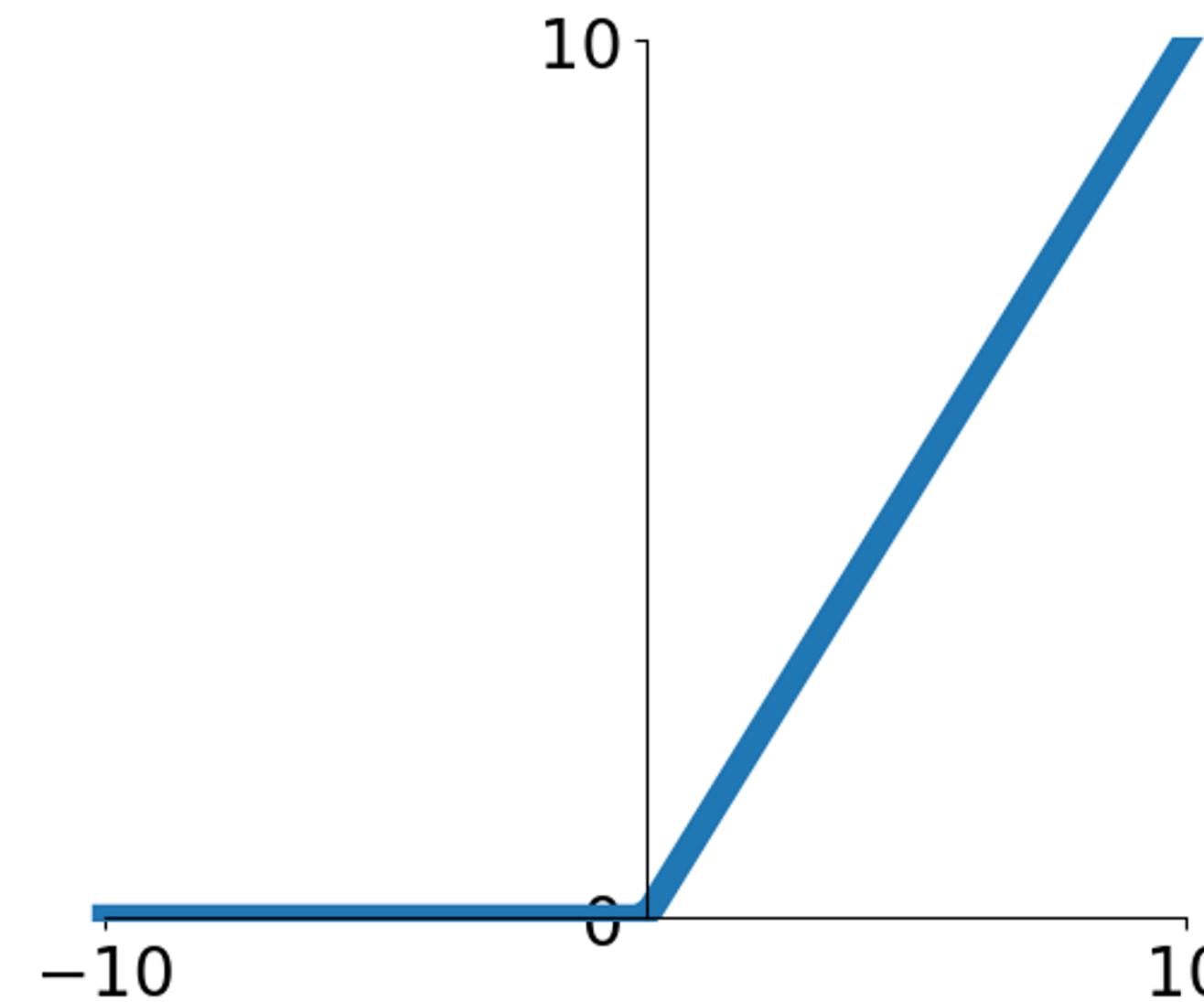
# Activation Functions

2-Layer Neural Network

$$f(x) = W_2 \max(0, W_1 x + b_1) + b_2$$

The auction  $ReLU(z) = \max(0, z)$   
is called “Rectified Linear Unit”

This is called the **activation function**  
of the neural network



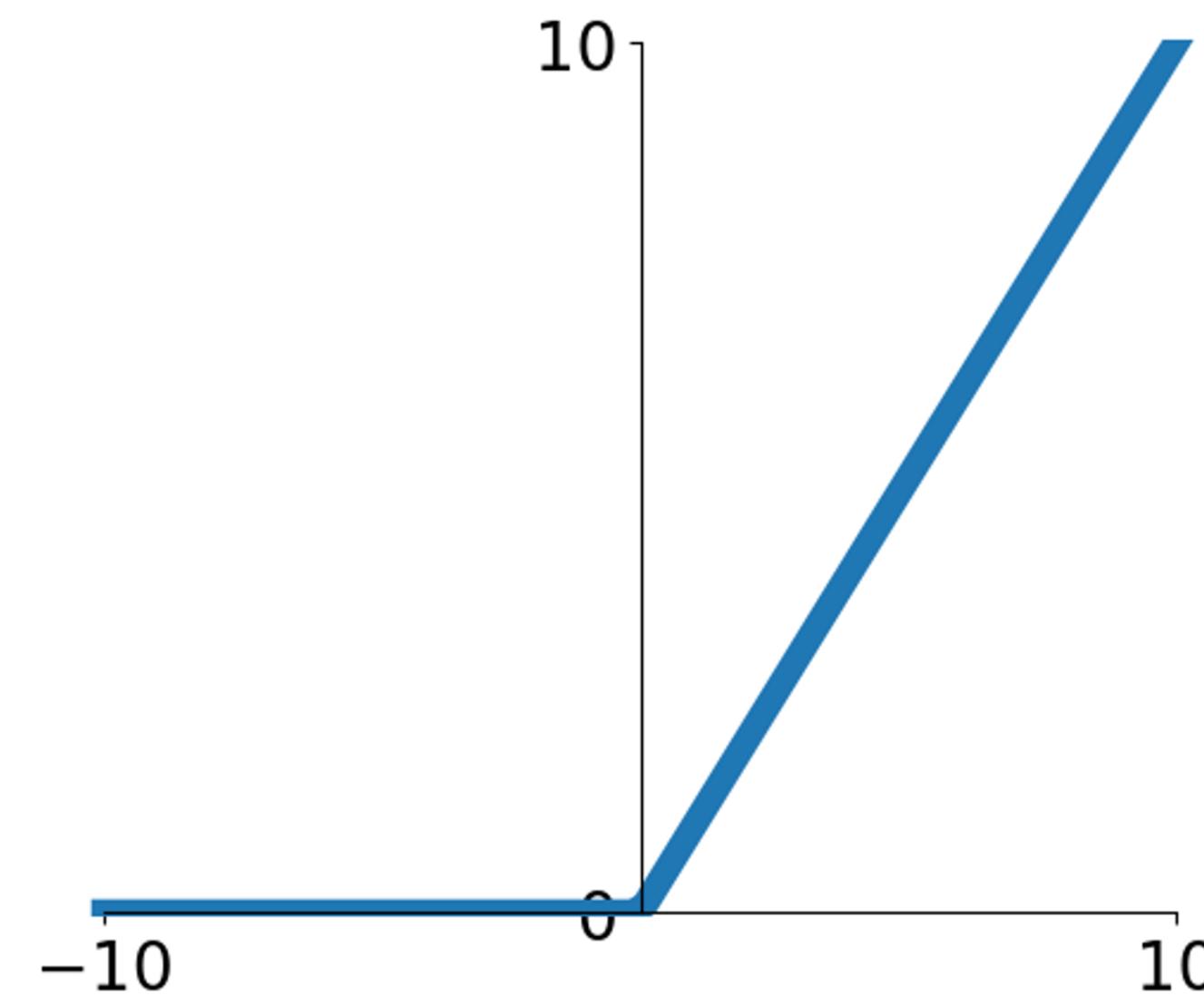
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**Q:** What happens if we build a neural network with no activation function?

$$f(x) = W_2(W_1 x + b_1) + b_2$$

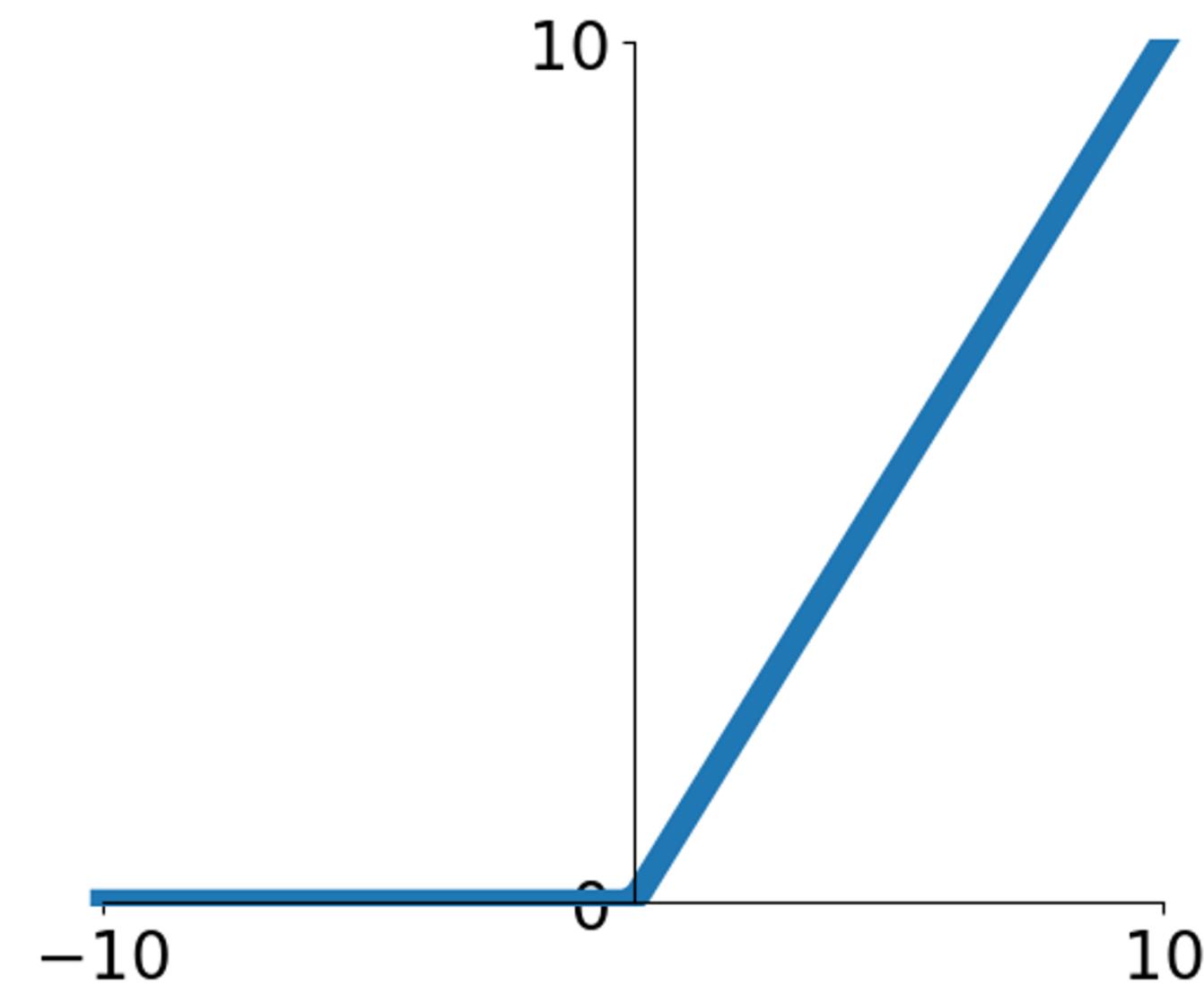
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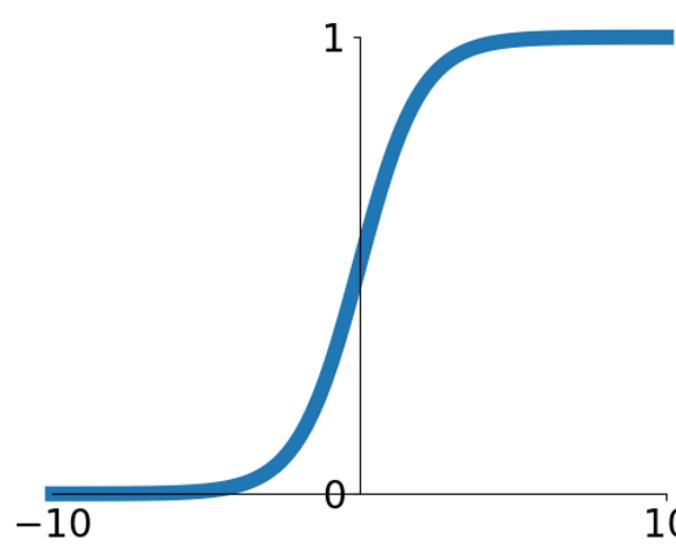
$$\begin{aligned} f(x) &= W_2(W_1 x + b_1) + b_2 \\ &= (W_1 W_2)x + (W_2 b_1 + b_2) \end{aligned}$$

**A:** We end up with a linear classifier

# Activation Functions

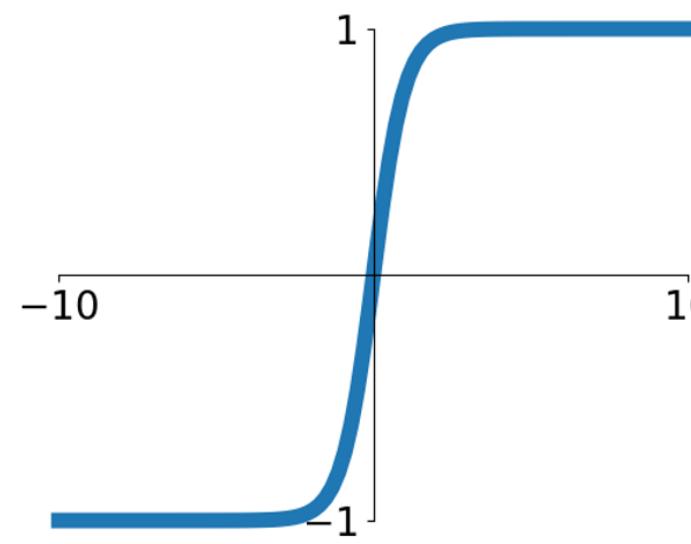
## Sigmoid

$$\sigma(x) = \frac{1}{1 + e^{-x}}$$



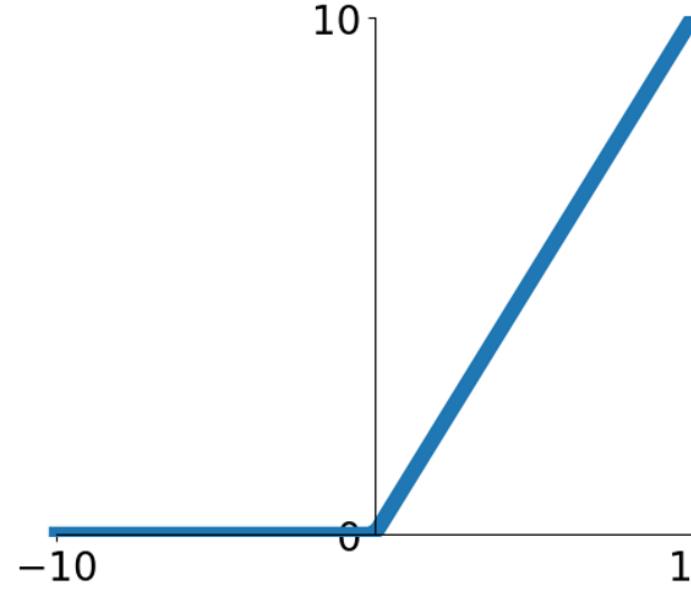
## tanh

$$\tanh(x) = \frac{e^{2x} - 1}{e^{2x} + 1}$$



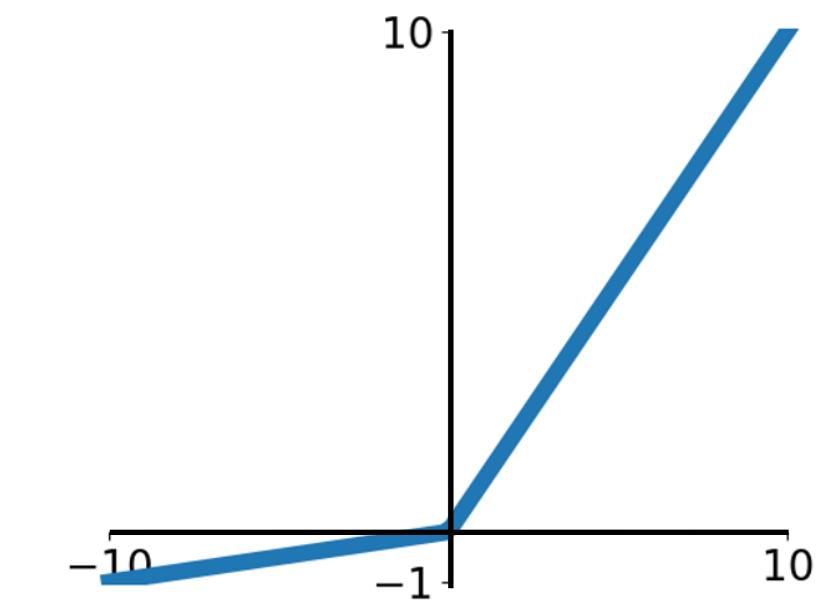
## ReLU

$$\max(0, x)$$



## Leaky ReLU

$$\max(0.2x, x)$$

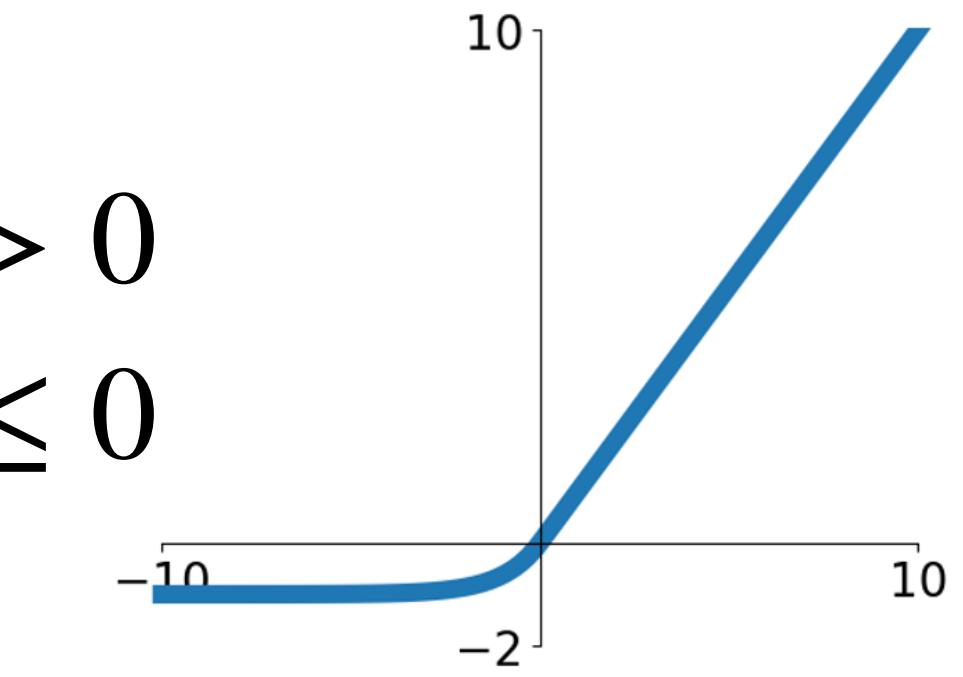


## Softplus

$$\log(1 + \exp(x))$$

## ELU

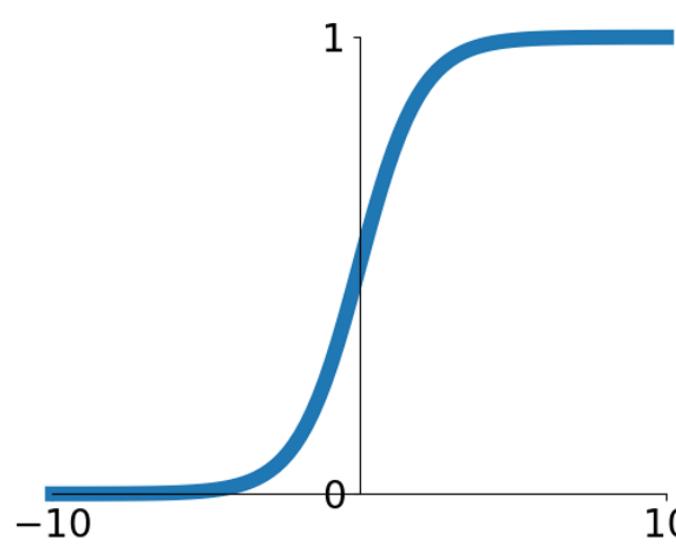
$$f(x) = \begin{cases} x, & x > 0 \\ \alpha(\exp(x) - 1), & x \leq 0 \end{cases}$$



# Activation Functions

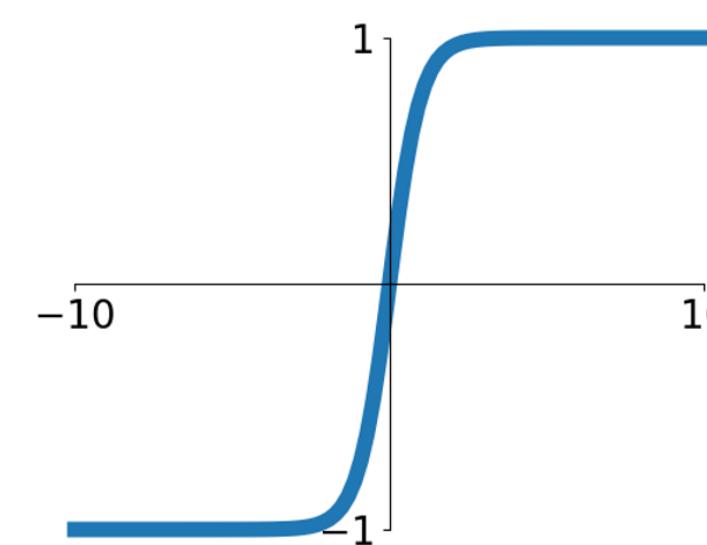
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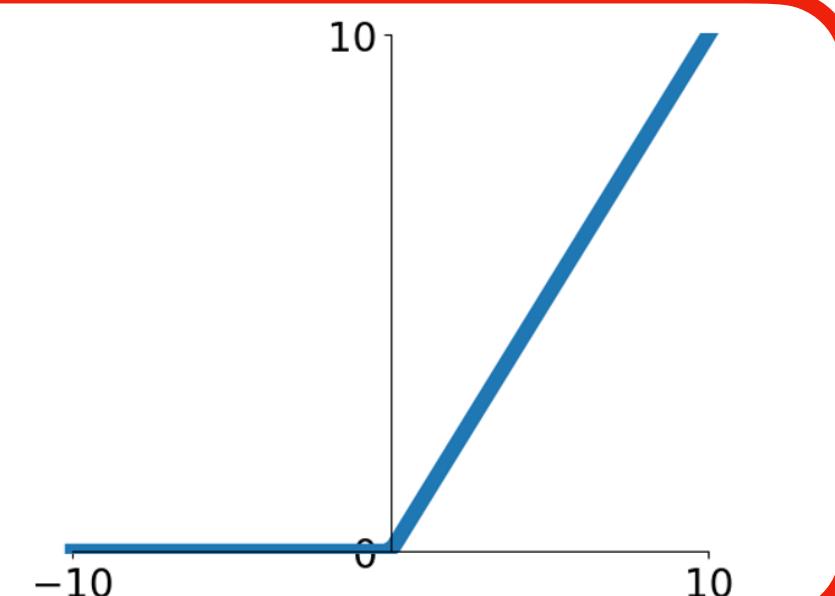
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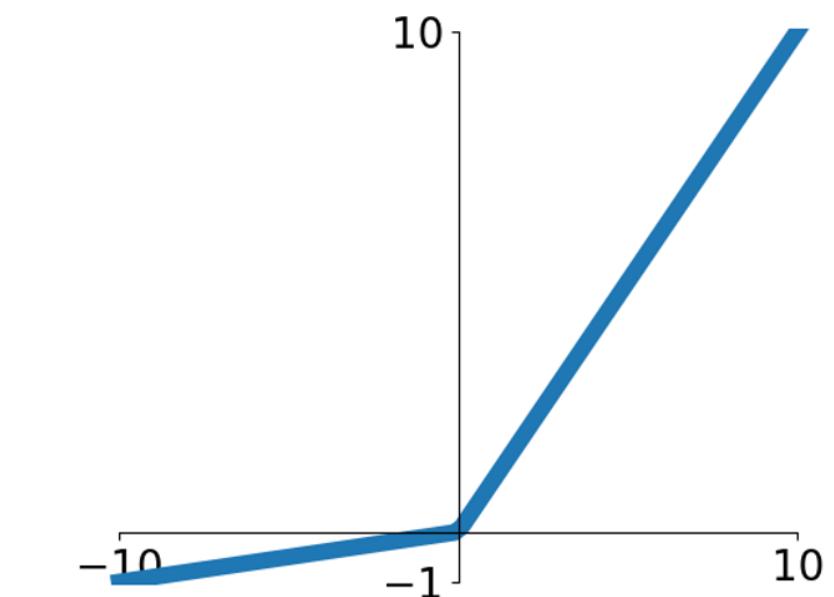
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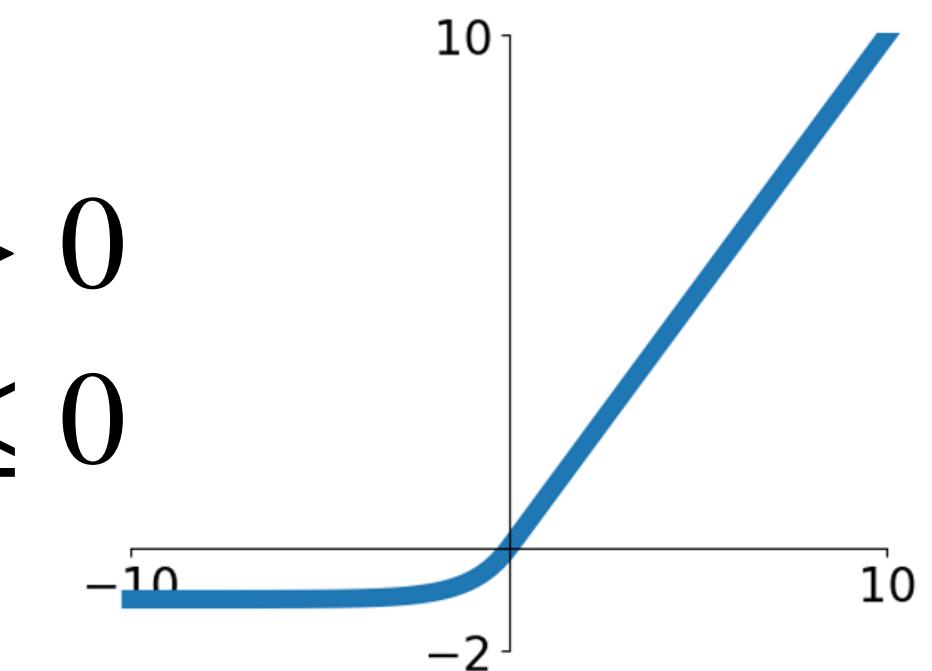


## Softplus

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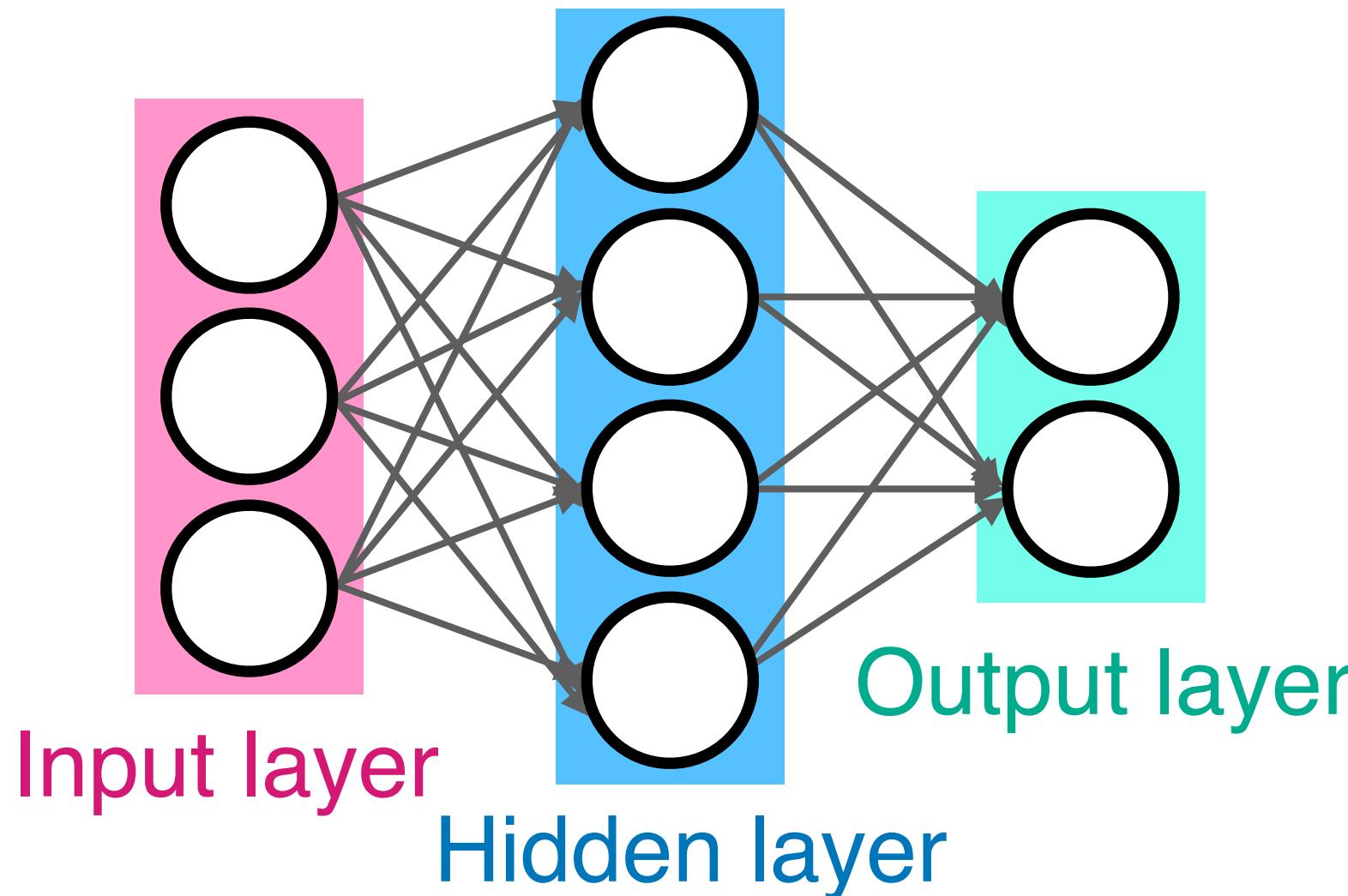
## ELU

$$f(x) = \begin{cases} x, & x > 0 \\ \alpha(\exp(x) - 1), & x \leq 0 \end{cases}$$



ReLU is a good default choice for most problems

# Neural Net in <20 lines!



Initialize weights  
and data

Compute loss (Sigmoid  
activation, L2 loss)

Compute gradients

SGD step

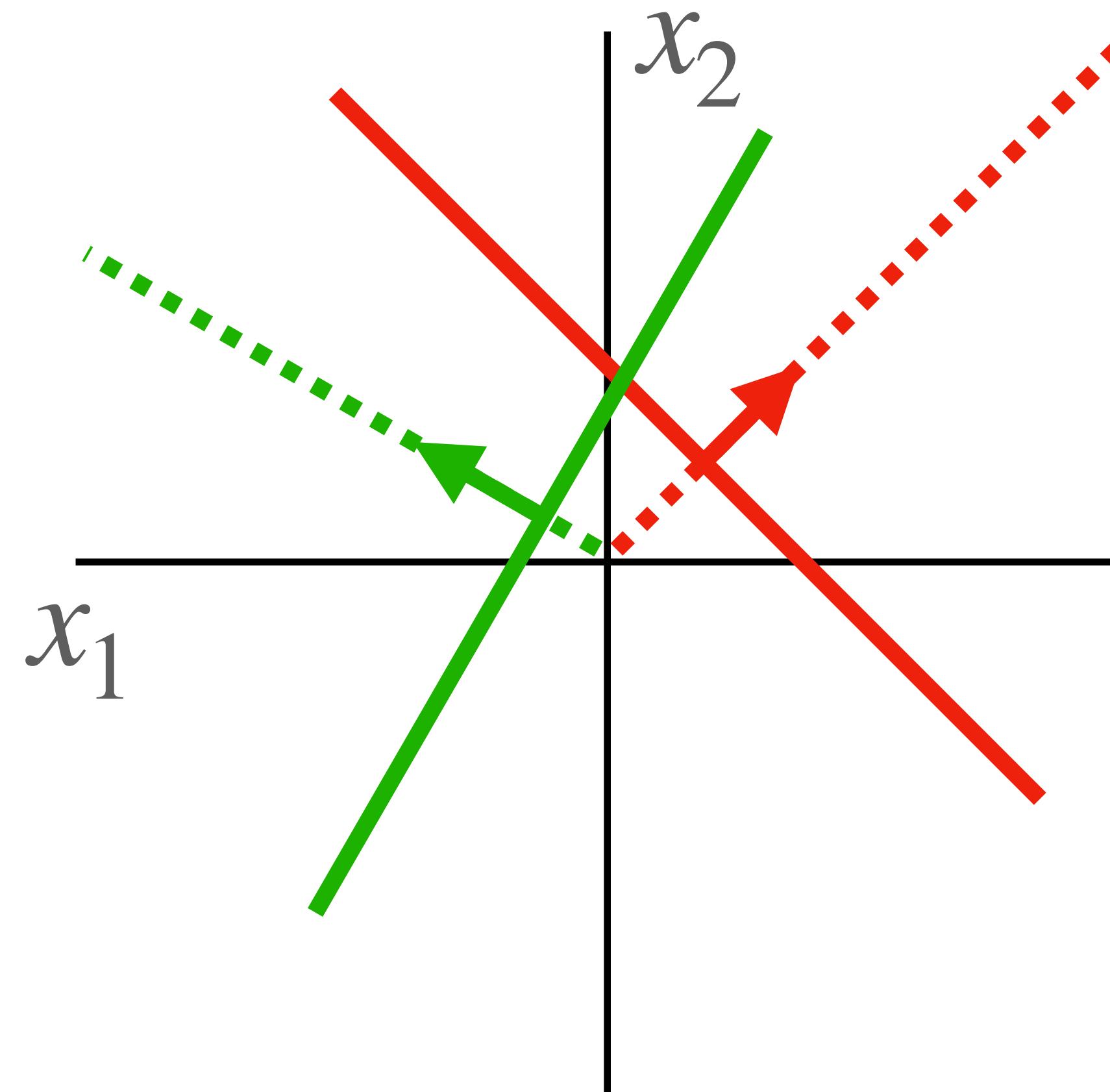
```

1 import numpy as np
2 from numpy.random import randn
3
4 N, Din, H, Dout = 64, 1000, 100, 10
5 x, y = randn(N, Din), randn(N, Dout)
6 w1, w2 = randn(Din, H), randn(H, Dout)
7 for t in range(10000):
8     h = 1.0 / (1.0 + np.exp(-x.dot(w1)))
9     y_pred = h.dot(w2)
10    loss = np.square(y_pred - y).sum()
11    dy_pred = 2.0 * (y_pred - y)
12    dw2 = h.T.dot(dy_pred)
13    dh = dy_pred.dot(w2.T)
14    dw1 = x.T.dot(dh * h * (1 - h))
15    w1 -= 1e-4 * dw1
16    w2 -= 1e-4 * dw2

```

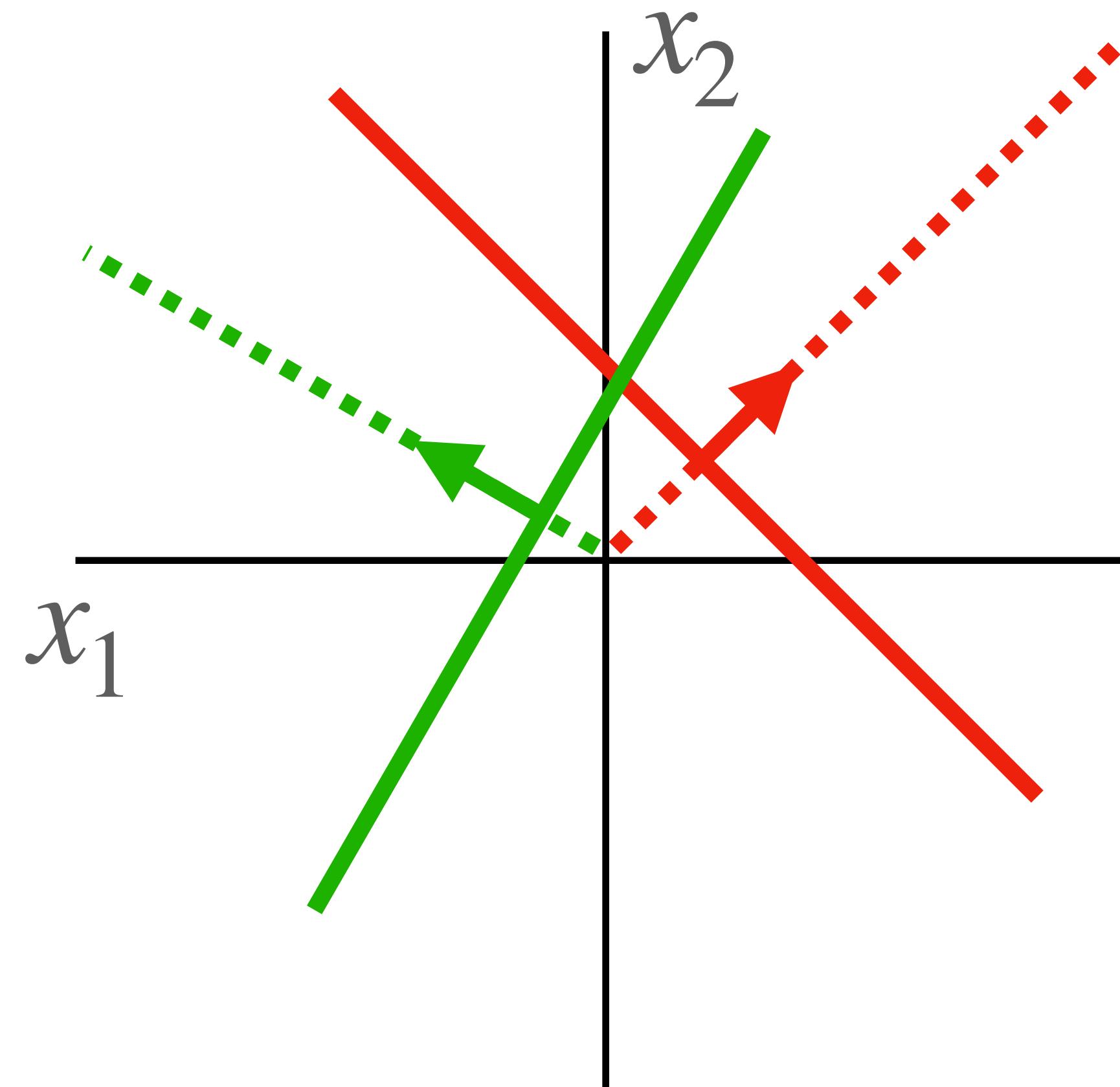
# Space Warping

Consider a linear transform:  $h = Wx + b$   
where  $x, b, h$  are each 2-dimensional



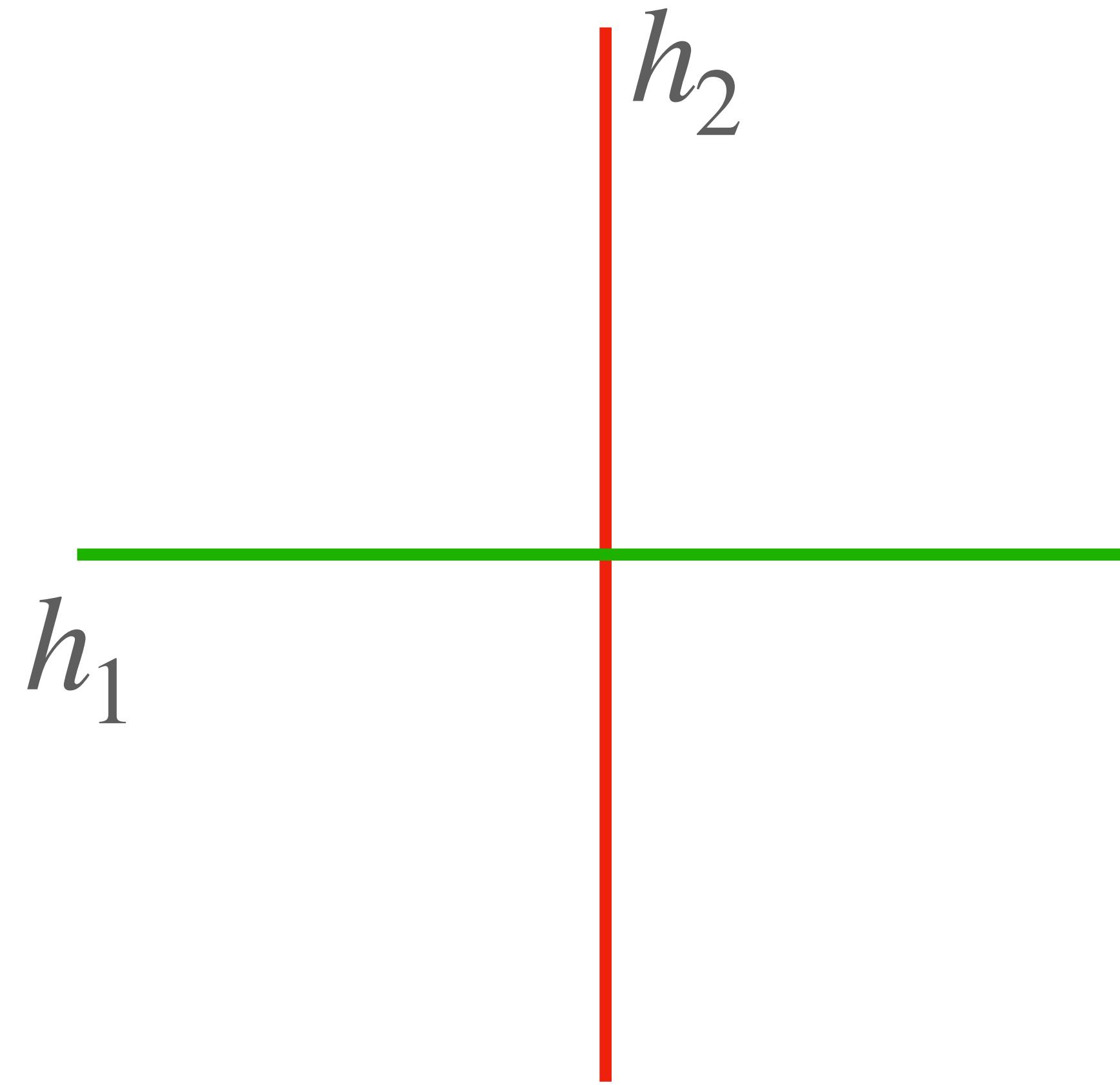
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Consider a linear transform:  $h = Wx + b$   
where  $x, b, h$  are each 2-dimensional



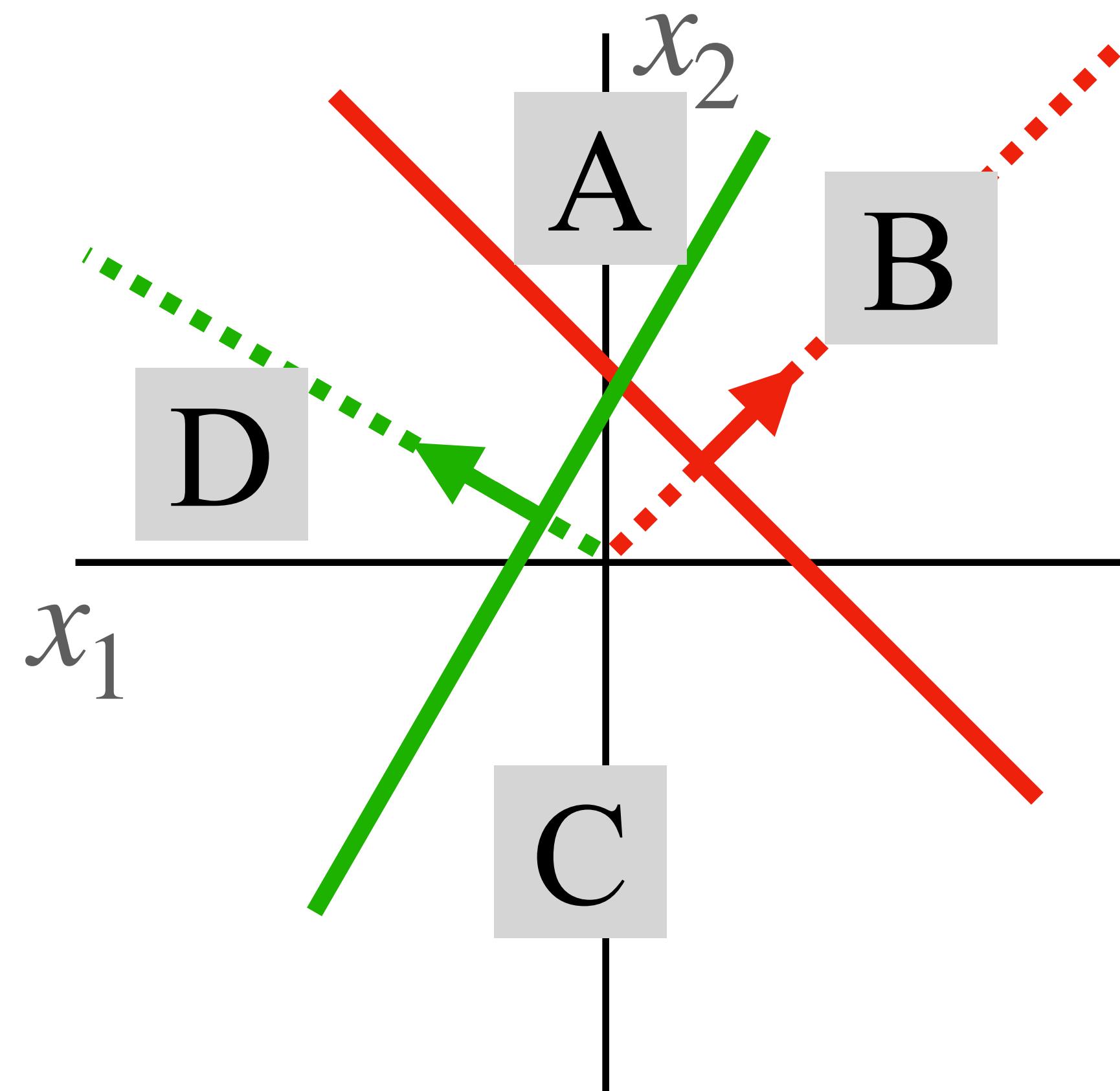
Feature transform:

$$h = Wx + b$$



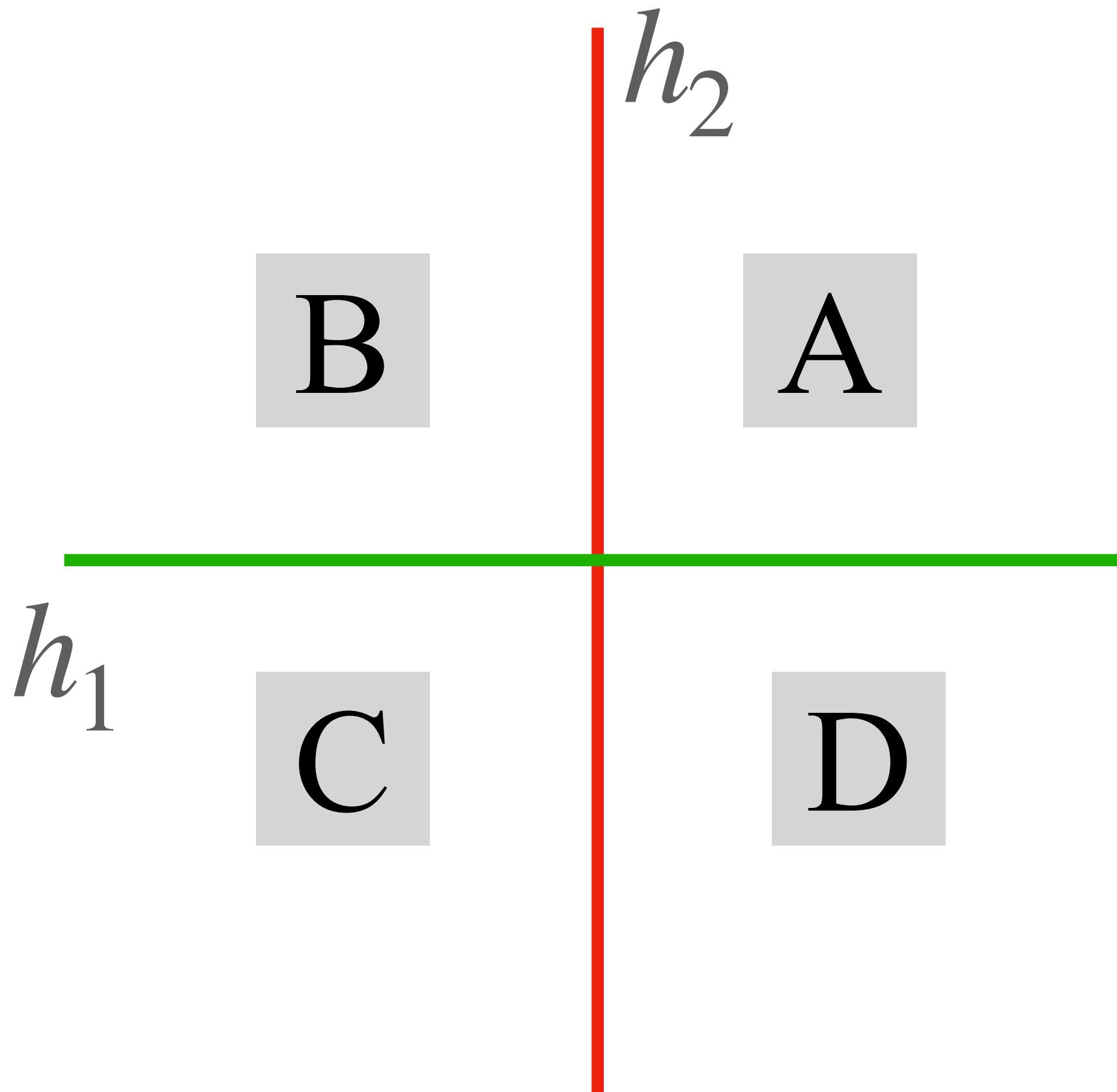
# Space Warping

Consider a linear transform:  $h = Wx + b$   
where  $x, b, h$  are each 2-dimensional



Feature transform:

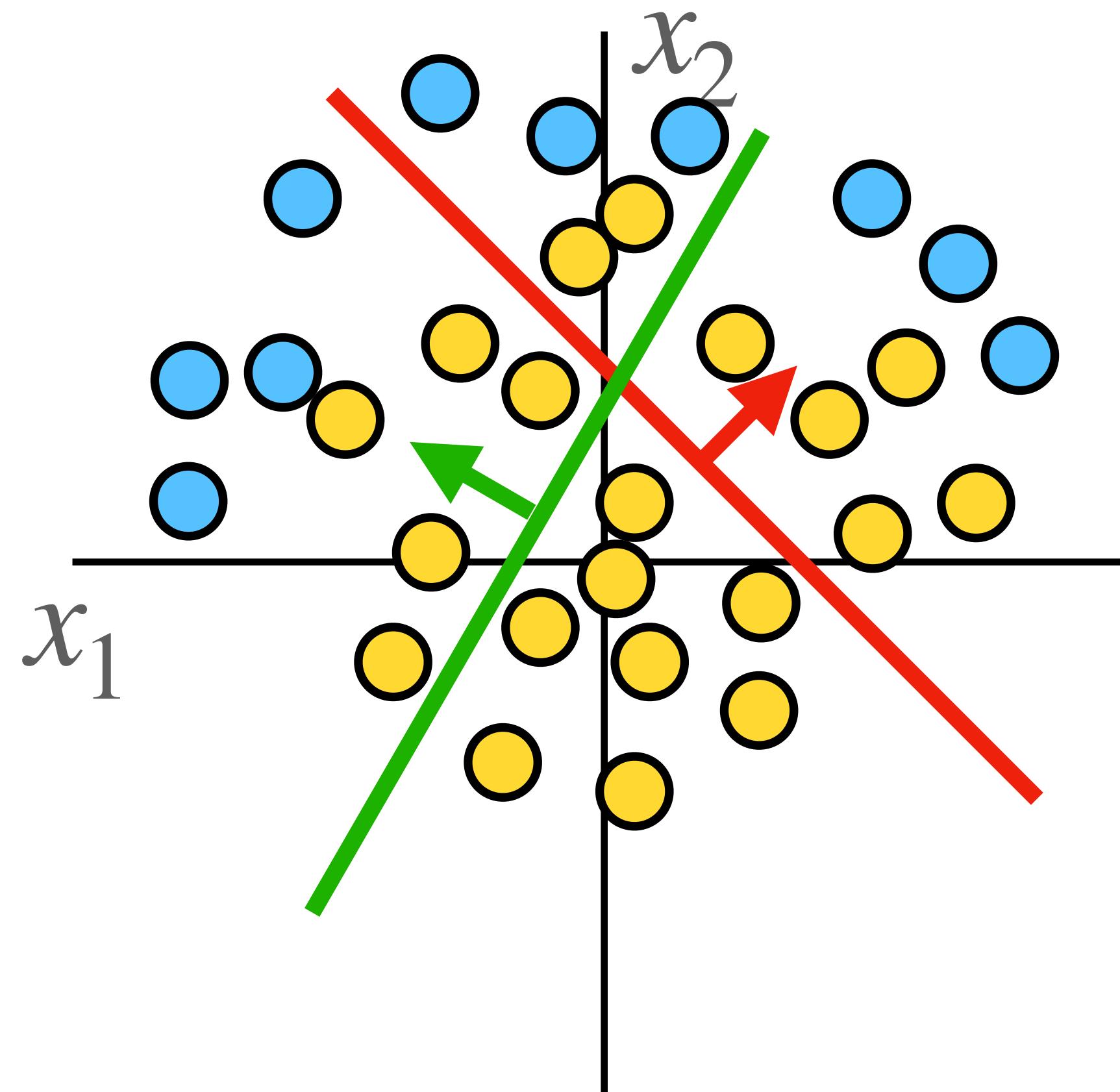
$$h = Wx + b$$



# Space Warping

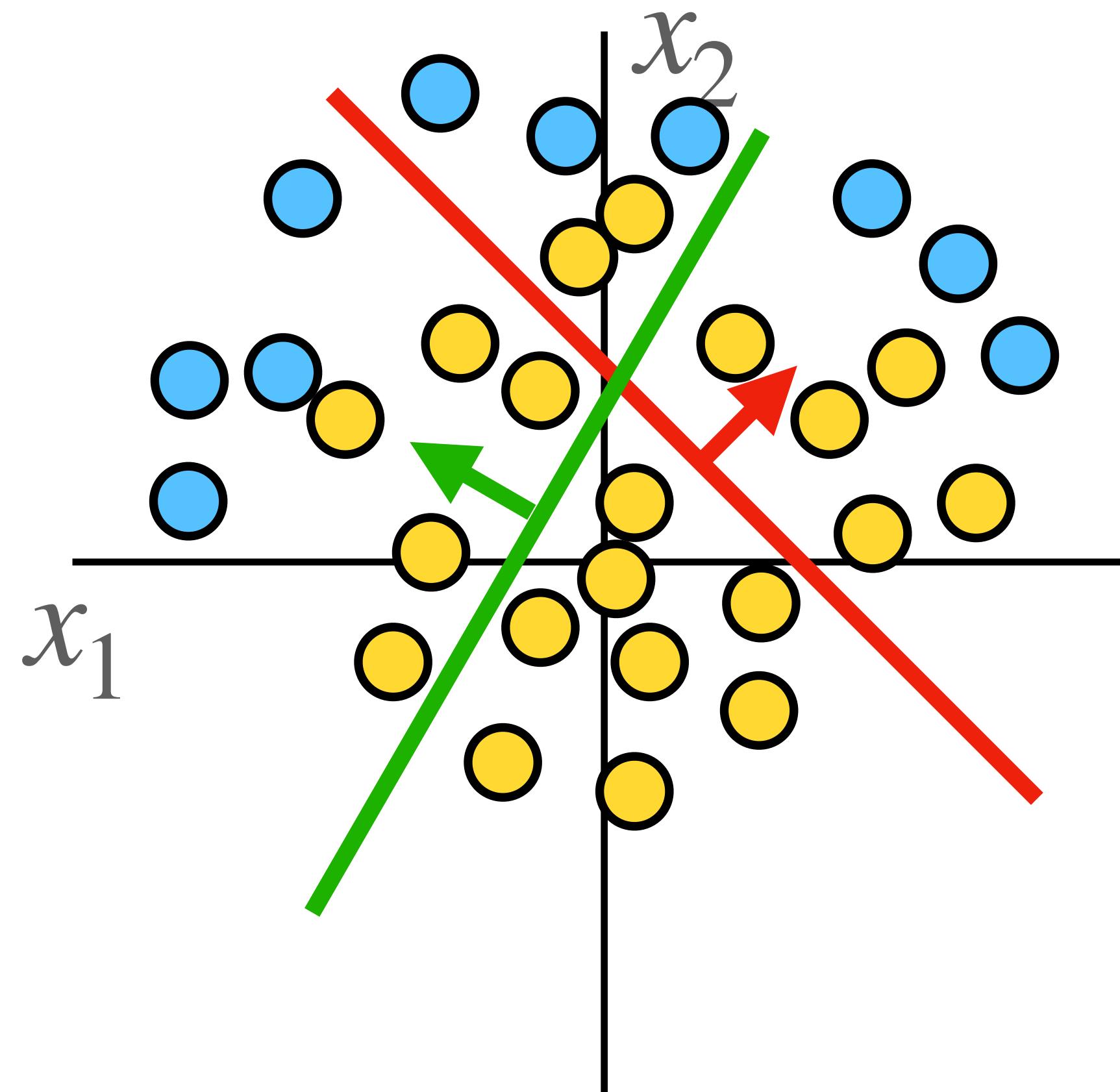
Points not linearly separable  
in original space

Consider a linear transform:  $h = Wx + b$   
where  $x, b, h$  are each 2-dimensional



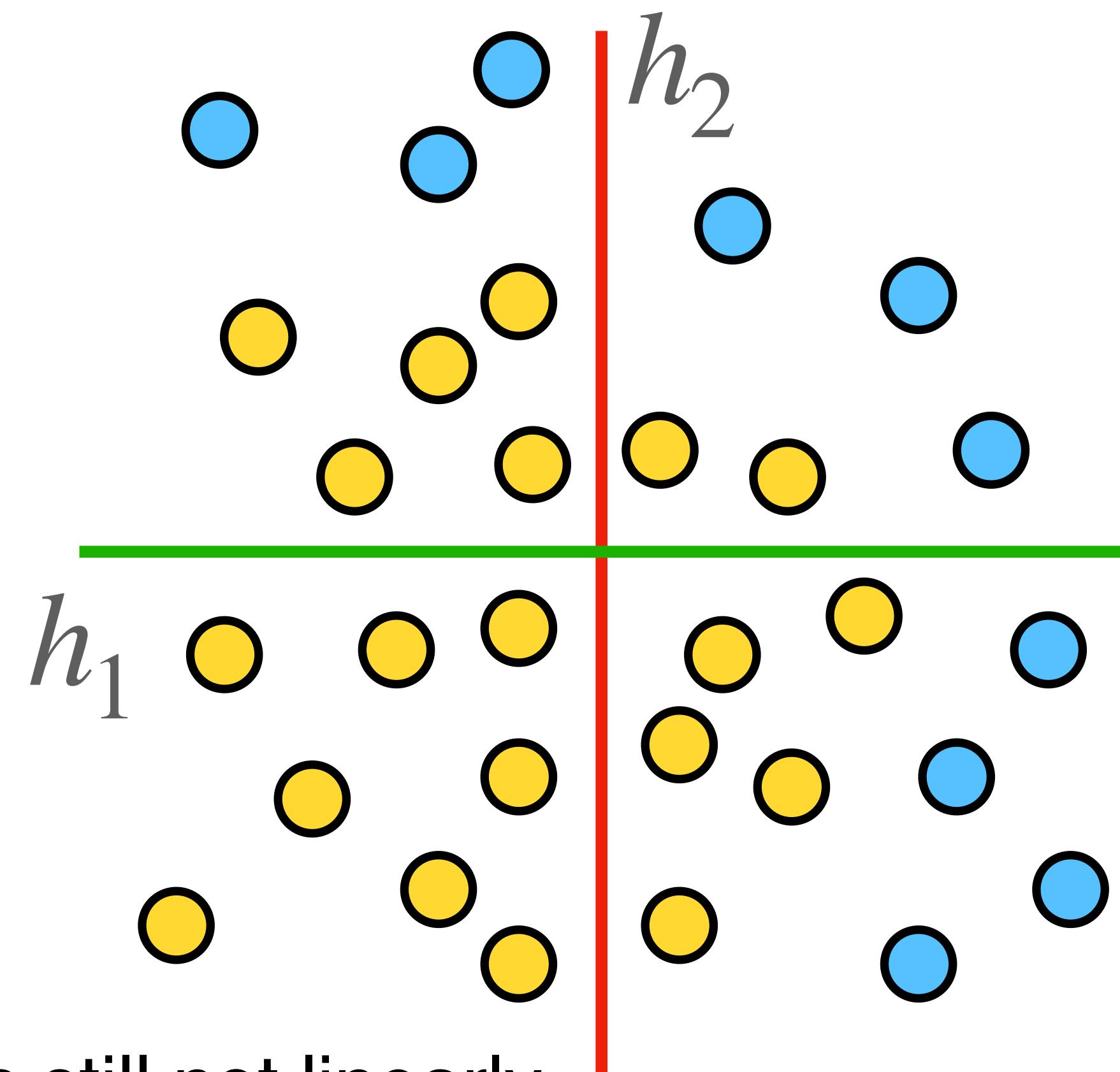
# Space Warping

Points not linearly separable  
in original space



Feature transform:  
 $h = Wx + b$

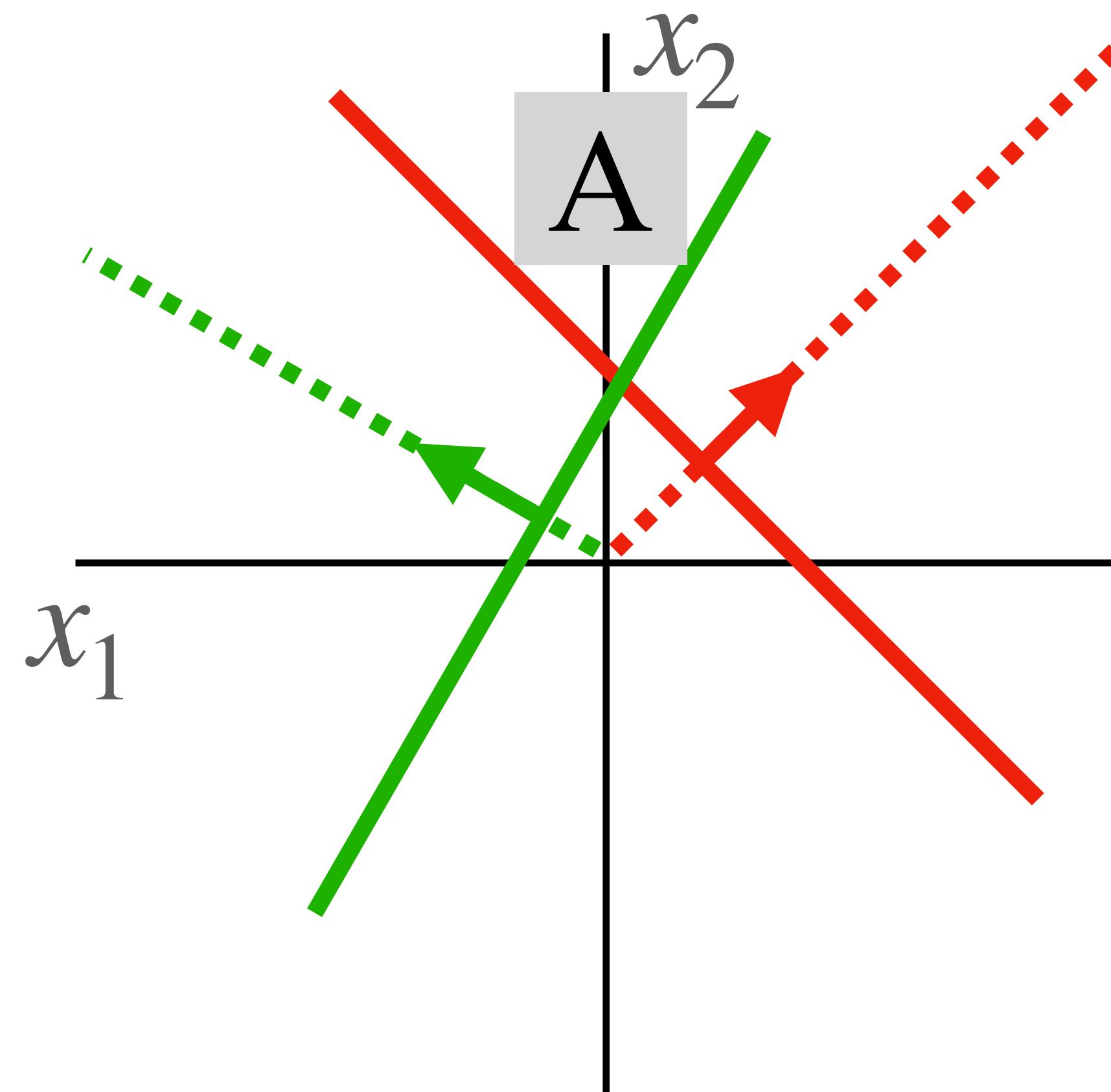
Consider a linear transform:  $h = Wx + b$   
where  $x, b, h$  are each 2-dimensional



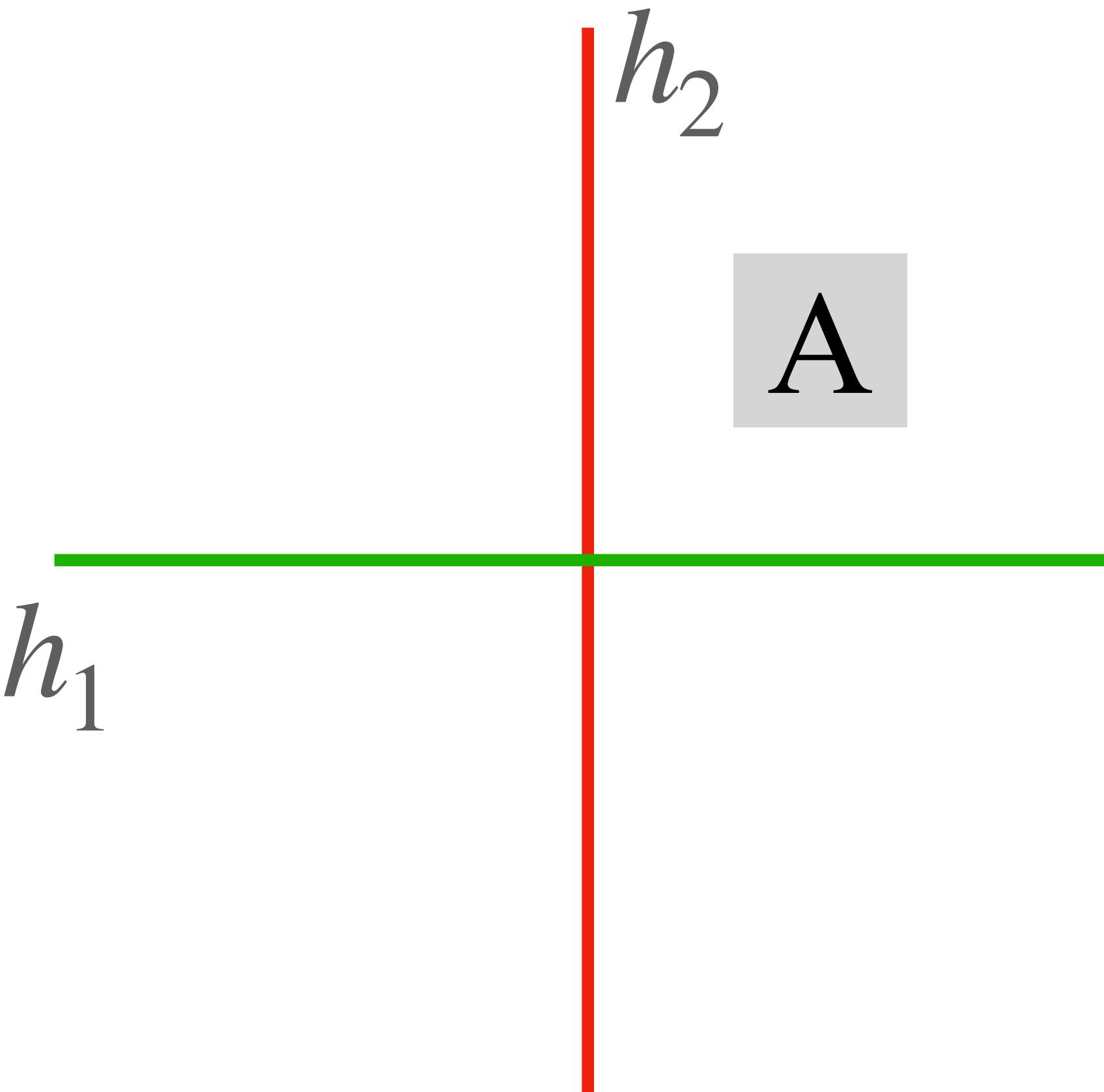
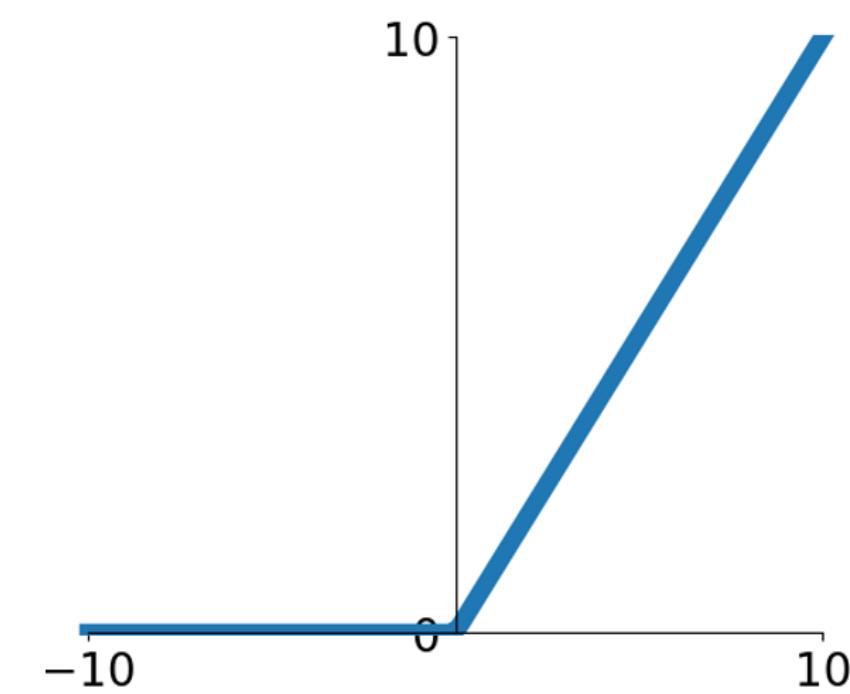
Points still not linearly  
separable in feature space

# Space Warping

Consider a neural net hidden layer:  $h = \text{ReLU}(Wx + b)$   
=  $\max(0, Wx + b)$  where  $x, b, h$  are each 2-dimensional

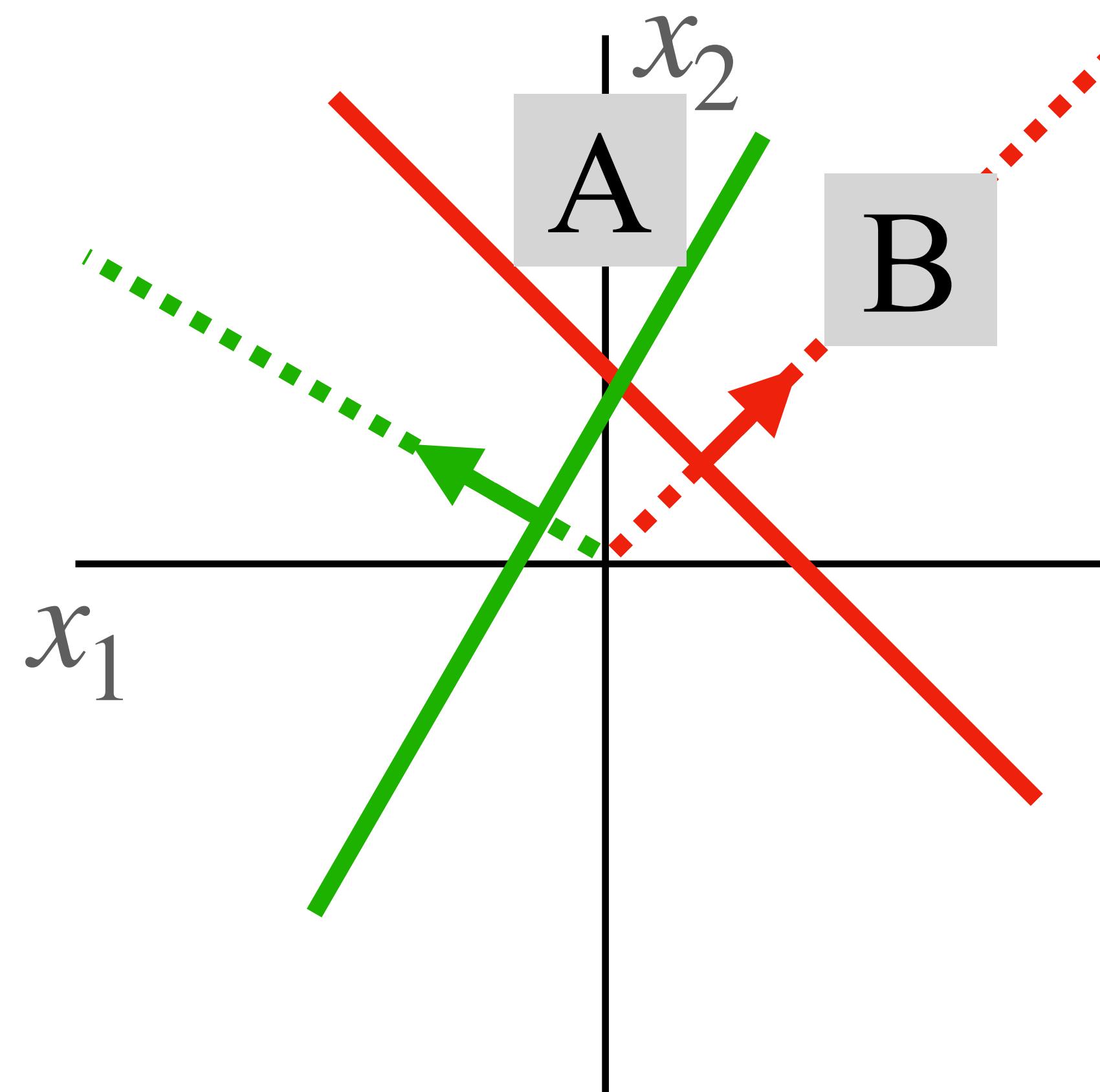


Feature transform:  
 $h = \text{ReLU}(Wx + b)$

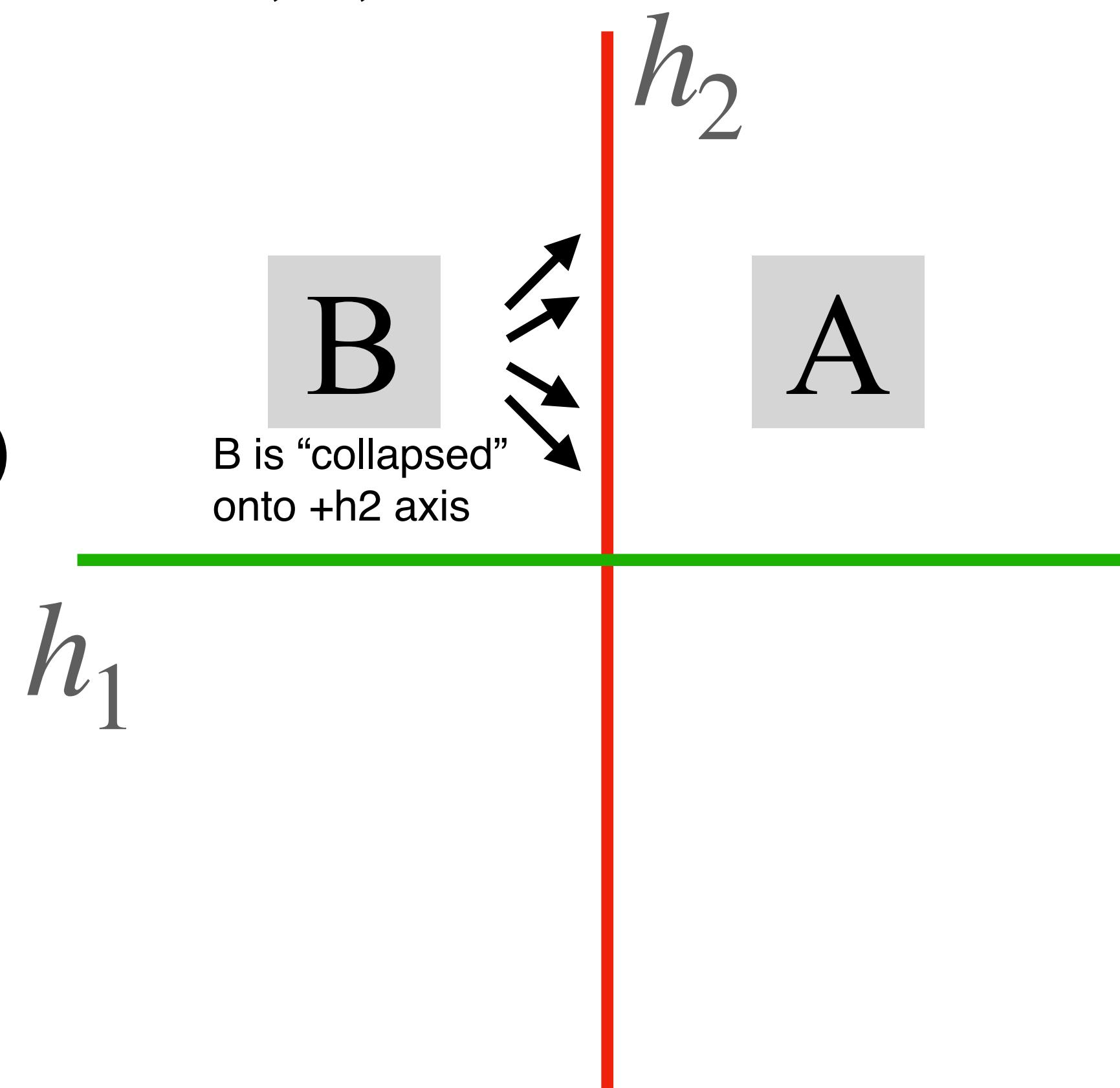
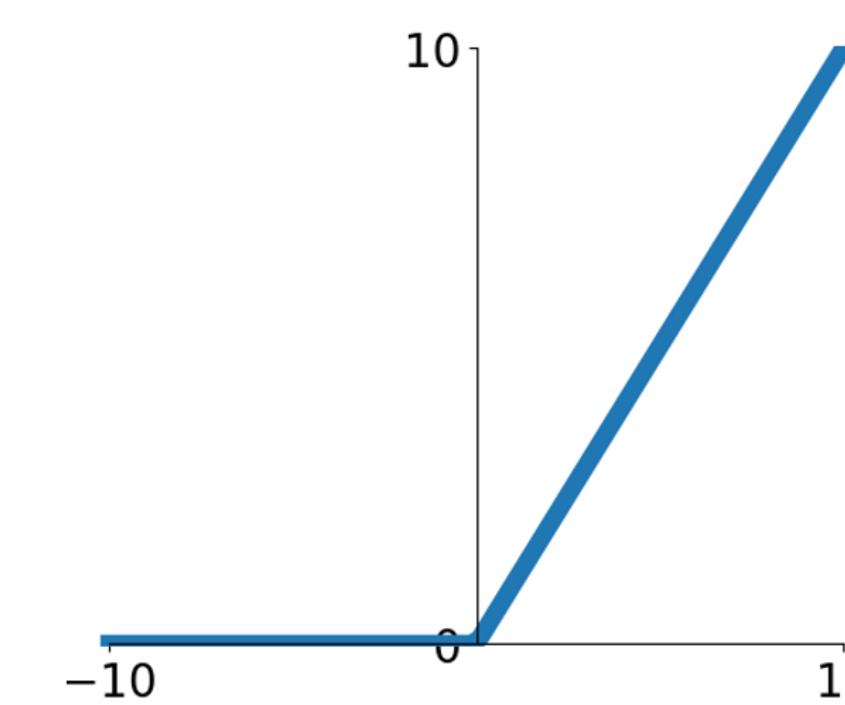


# Space Warping

Consider a neural net hidden layer:  $h = \text{ReLU}(Wx + b)$   
 $= \max(0, Wx + b)$  where  $x, b, h$  are each 2-dimensional

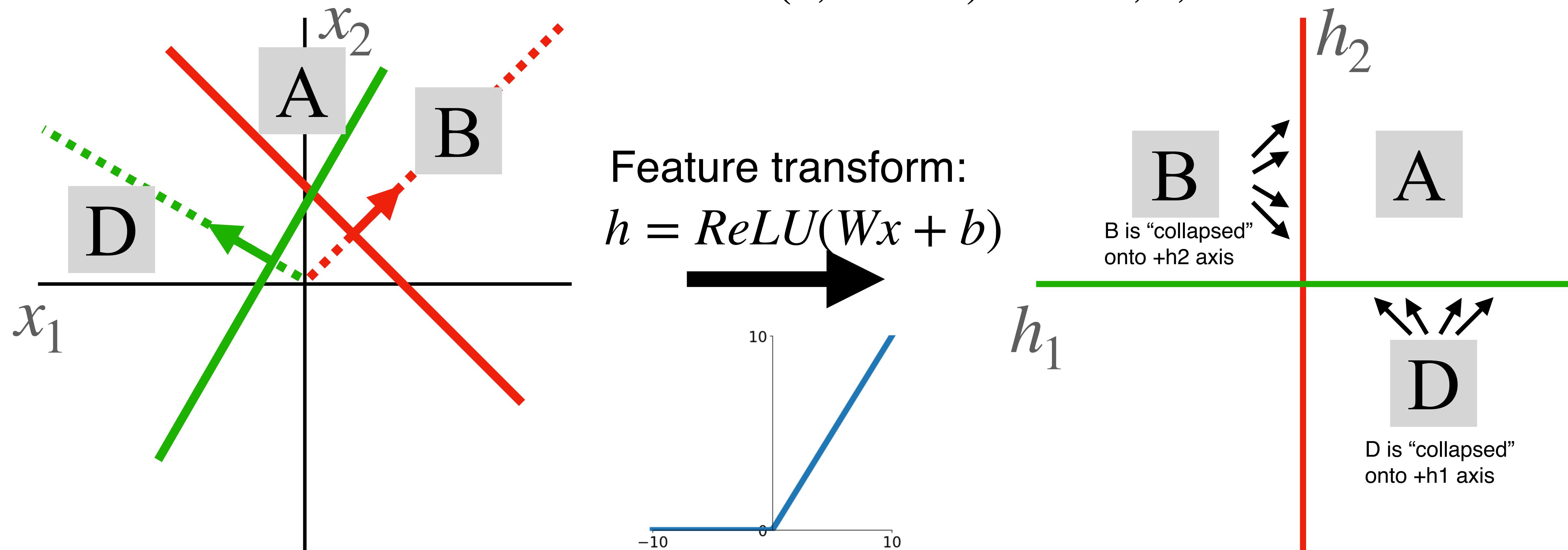


Feature transform:  
 $h = \text{ReLU}(Wx + b)$



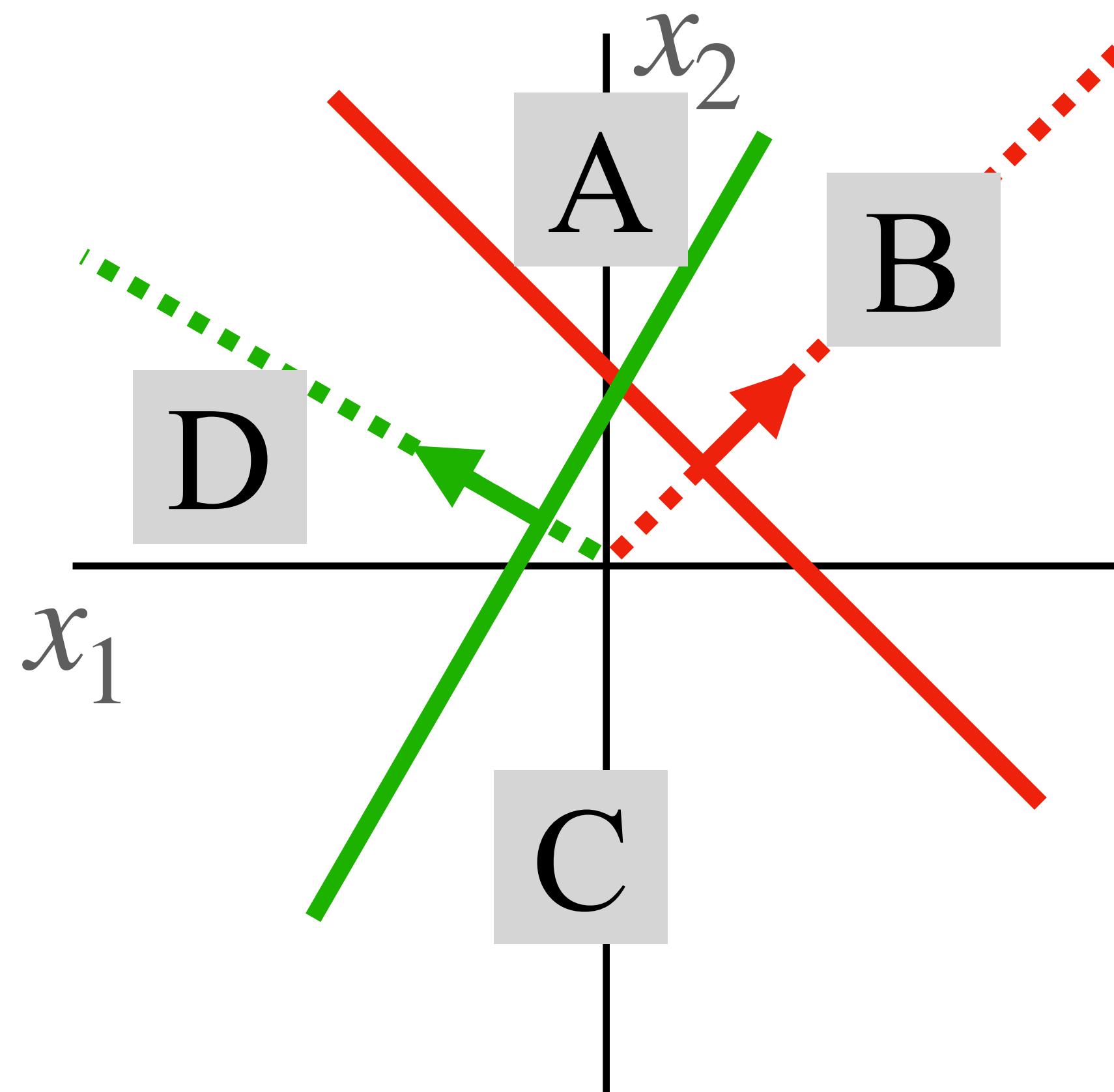
# Space Warping

Consider a neural net hidden layer:  $h = \text{ReLU}(Wx + b)$   
 $= \max(0, Wx + b)$  where  $x, b, h$  are each 2-dimensional

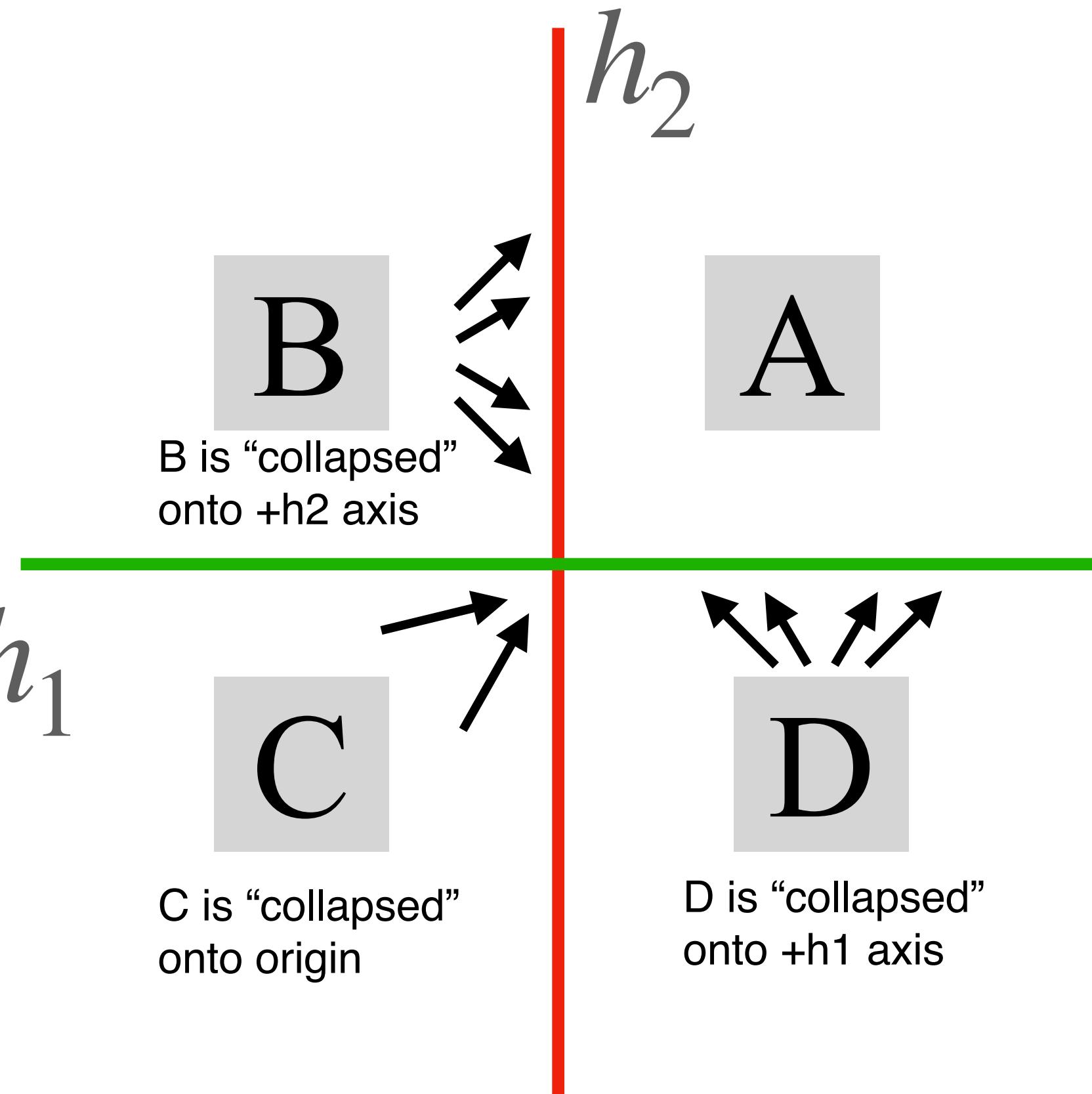
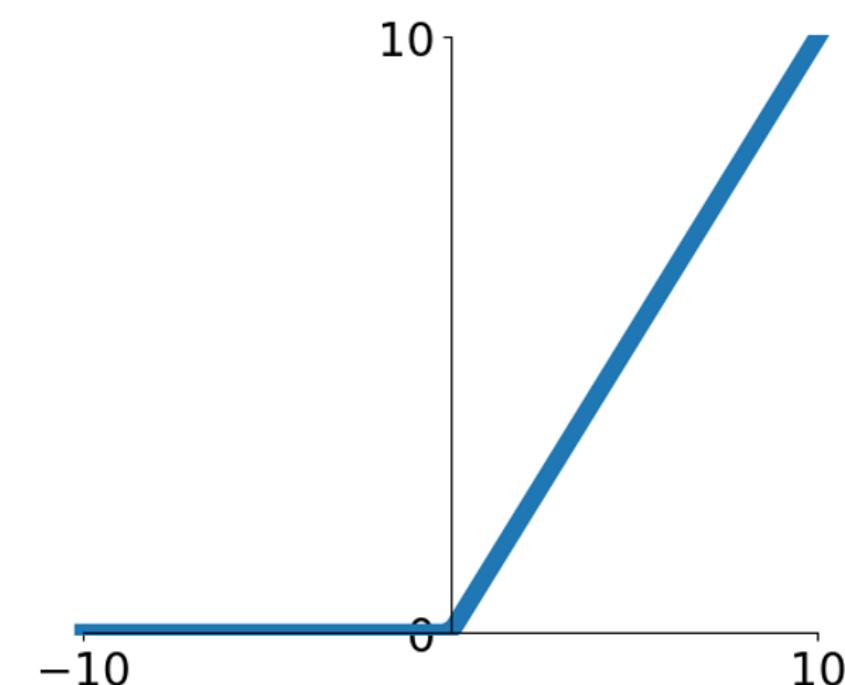


# Space Warping

Consider a neural net hidden layer:  $h = \text{ReLU}(Wx + b)$   
 $= \max(0, Wx + b)$  where  $x, b, h$  are each 2-dimensional

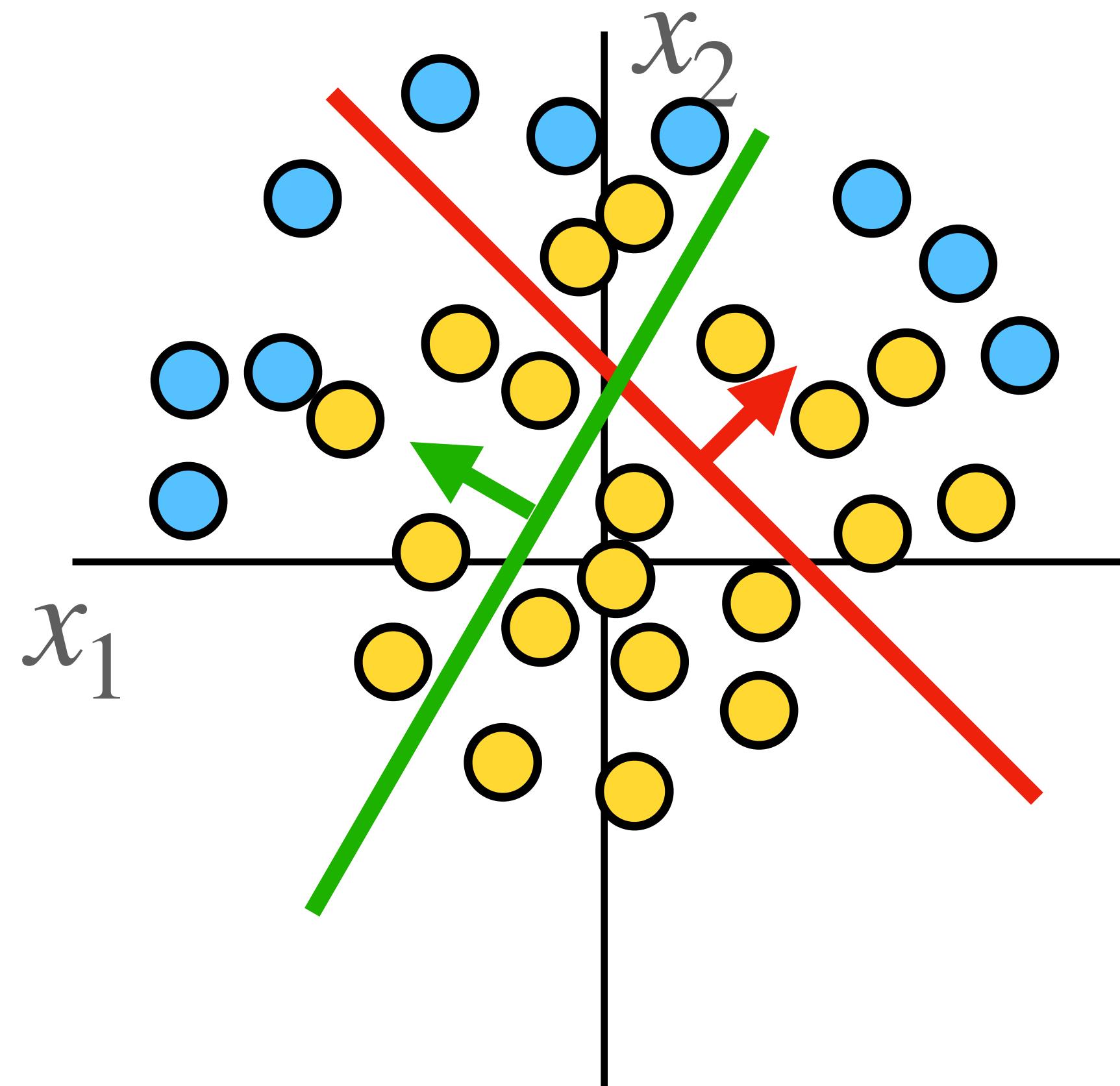


Feature transform:  
 $h = \text{ReLU}(Wx + b)$



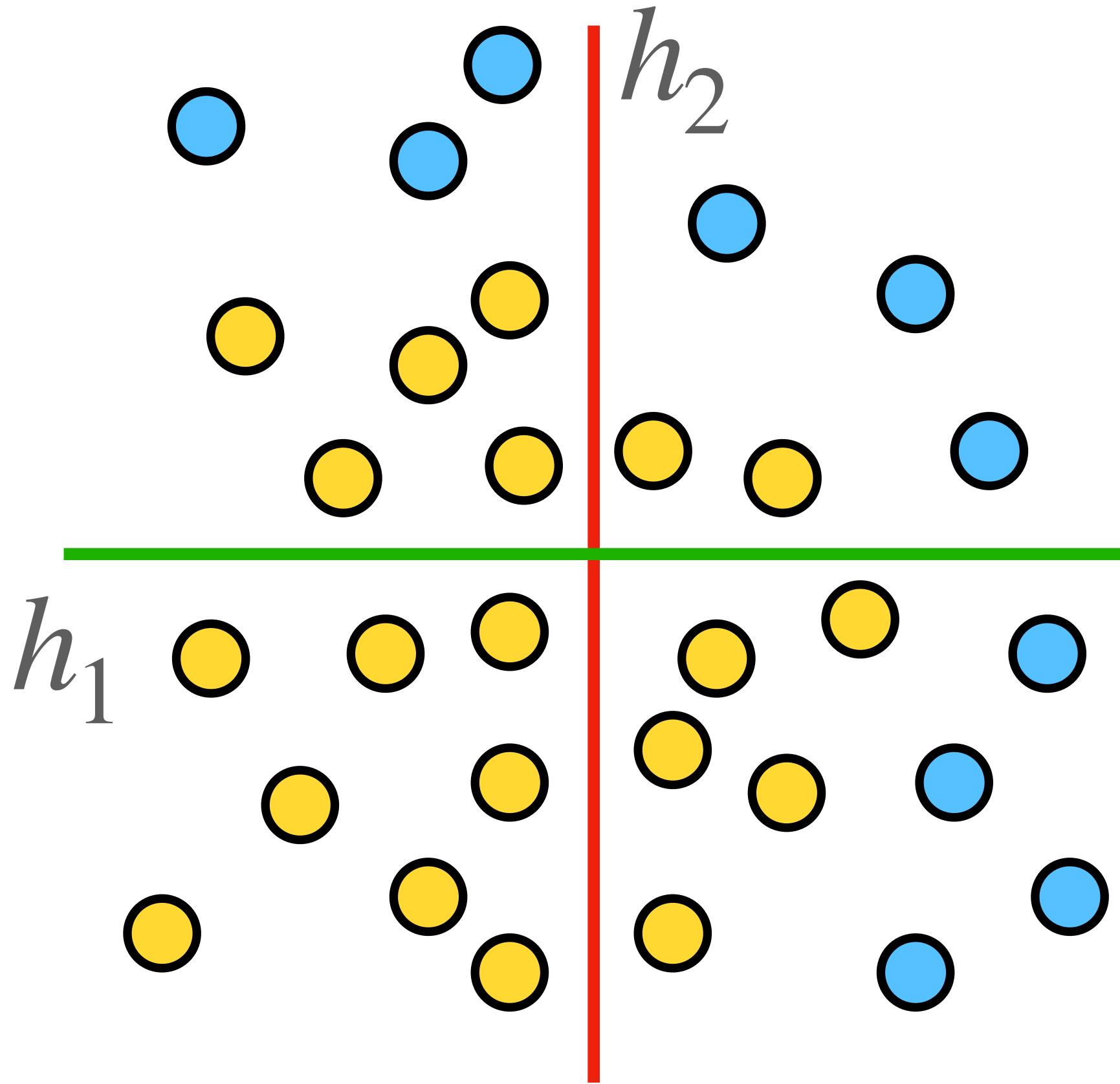
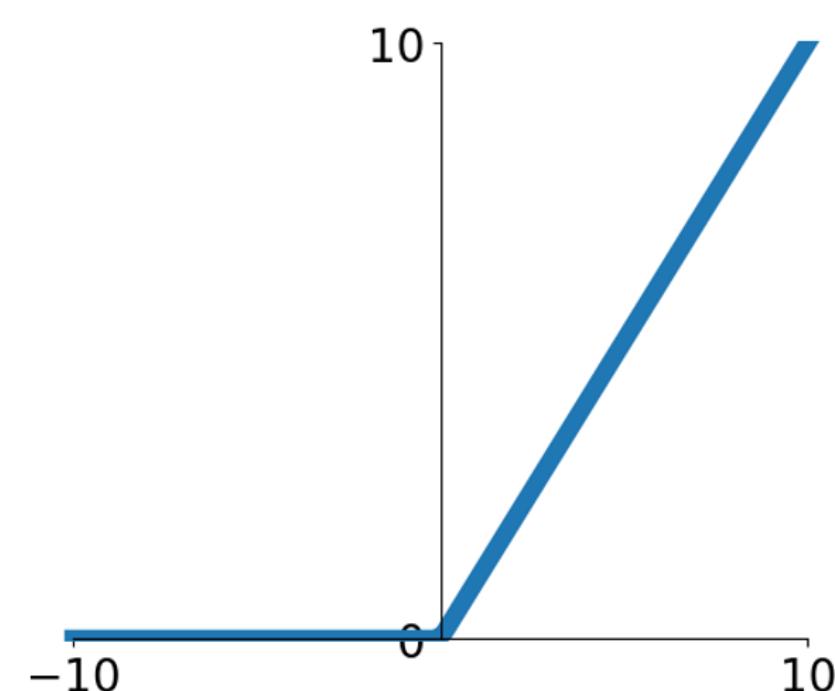
# Space Warping

Points not linearly separable  
in original space



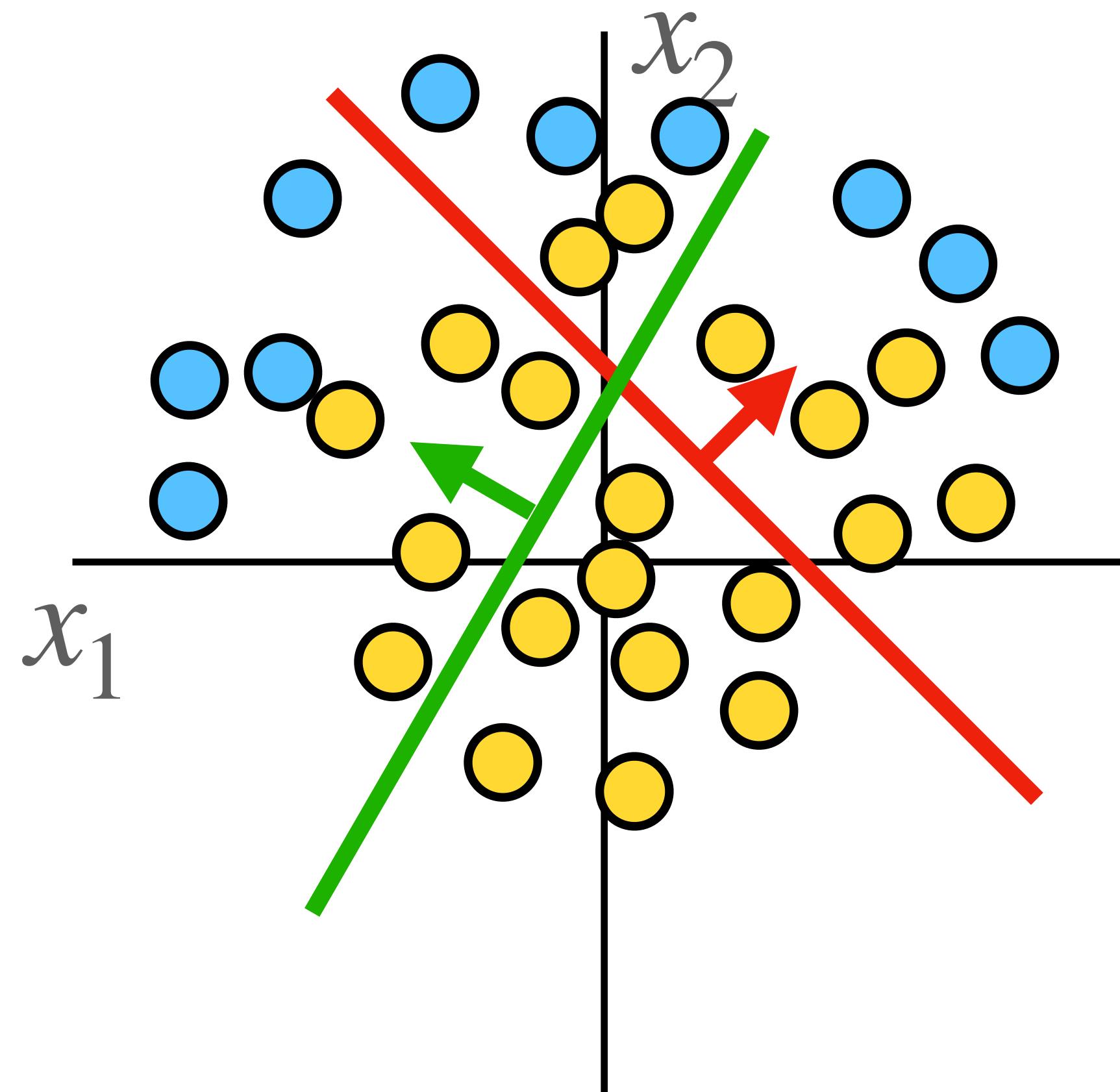
Consider a neural net hidden layer:  $h = \text{ReLU}(Wx + b)$   
 $= \max(0, Wx + b)$  where  $x, b, h$  are each 2-dimensional

Feature transform:  
 $h = \text{ReLU}(Wx + b)$



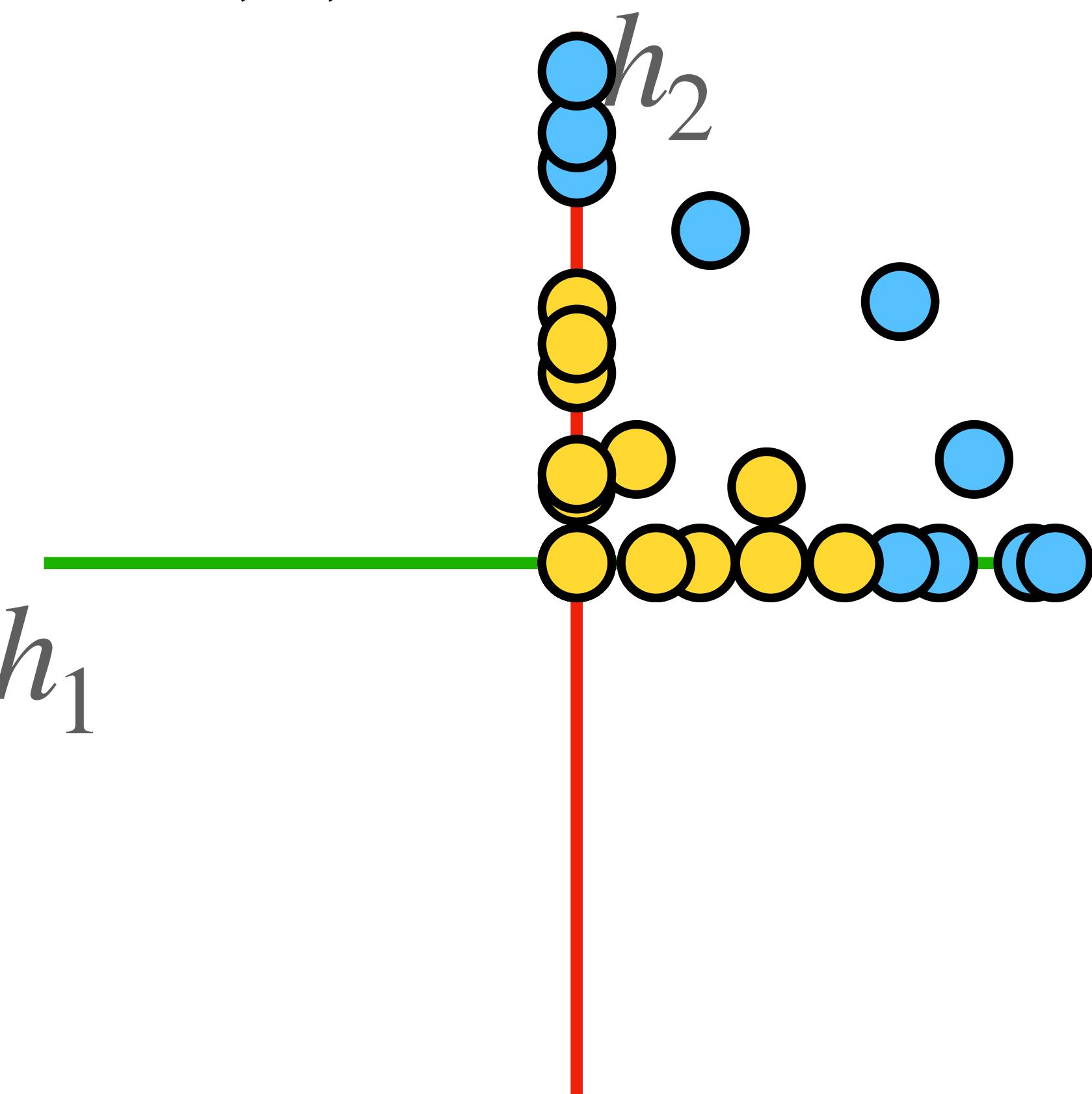
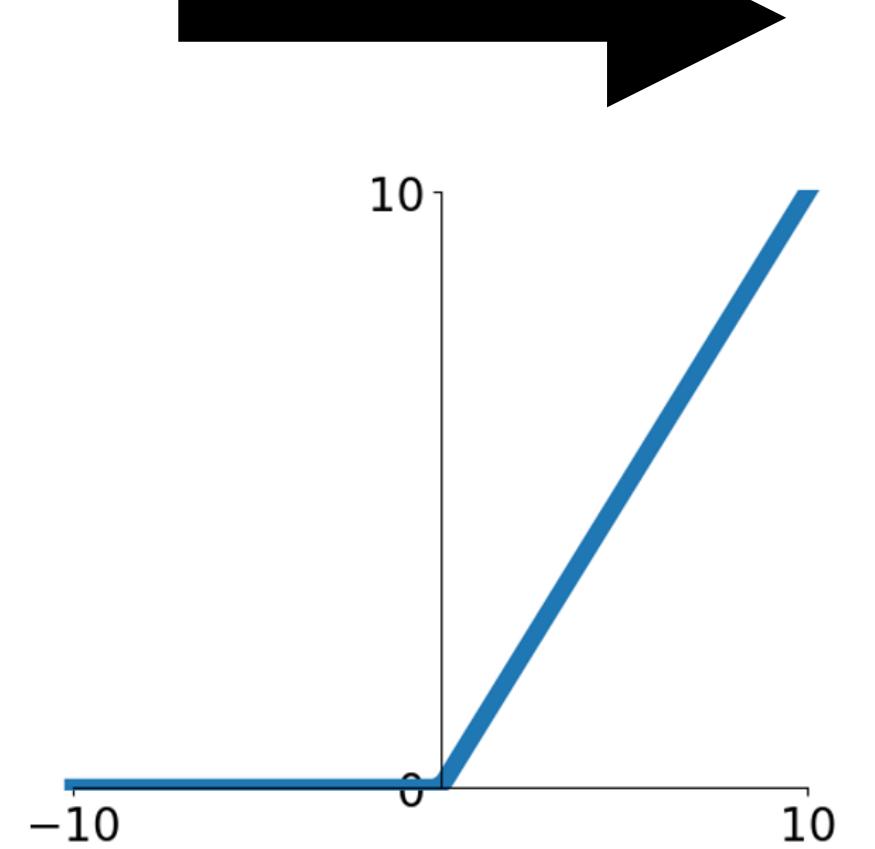
# Space Warping

Points not linearly separable  
in original space



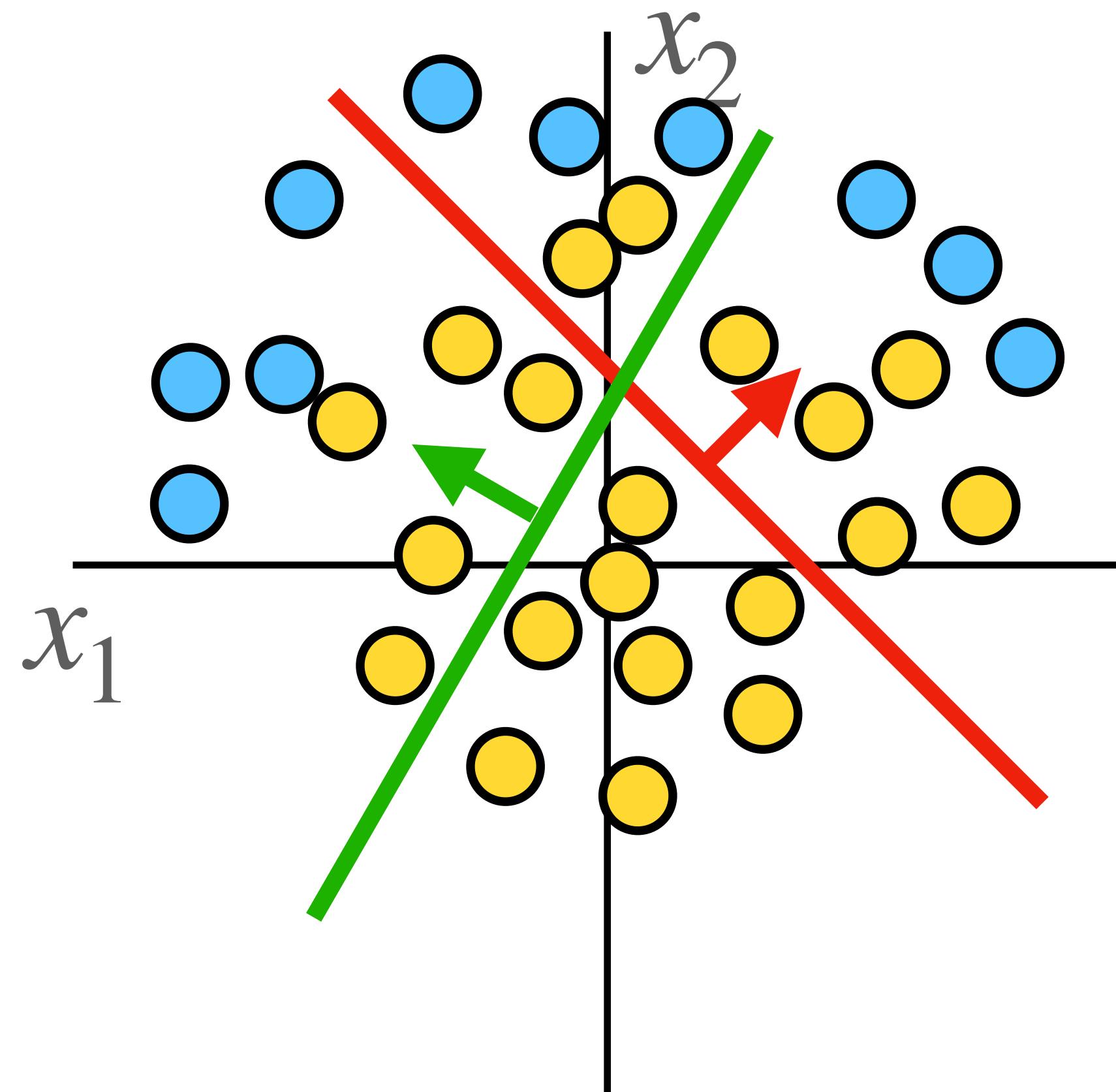
Consider a neural net hidden layer:  $h = \text{ReLU}(Wx + b)$   
 $= \max(0, Wx + b)$  where  $x, b, h$  are each 2-dimensional

Feature transform:  
 $h = \text{ReLU}(Wx + b)$



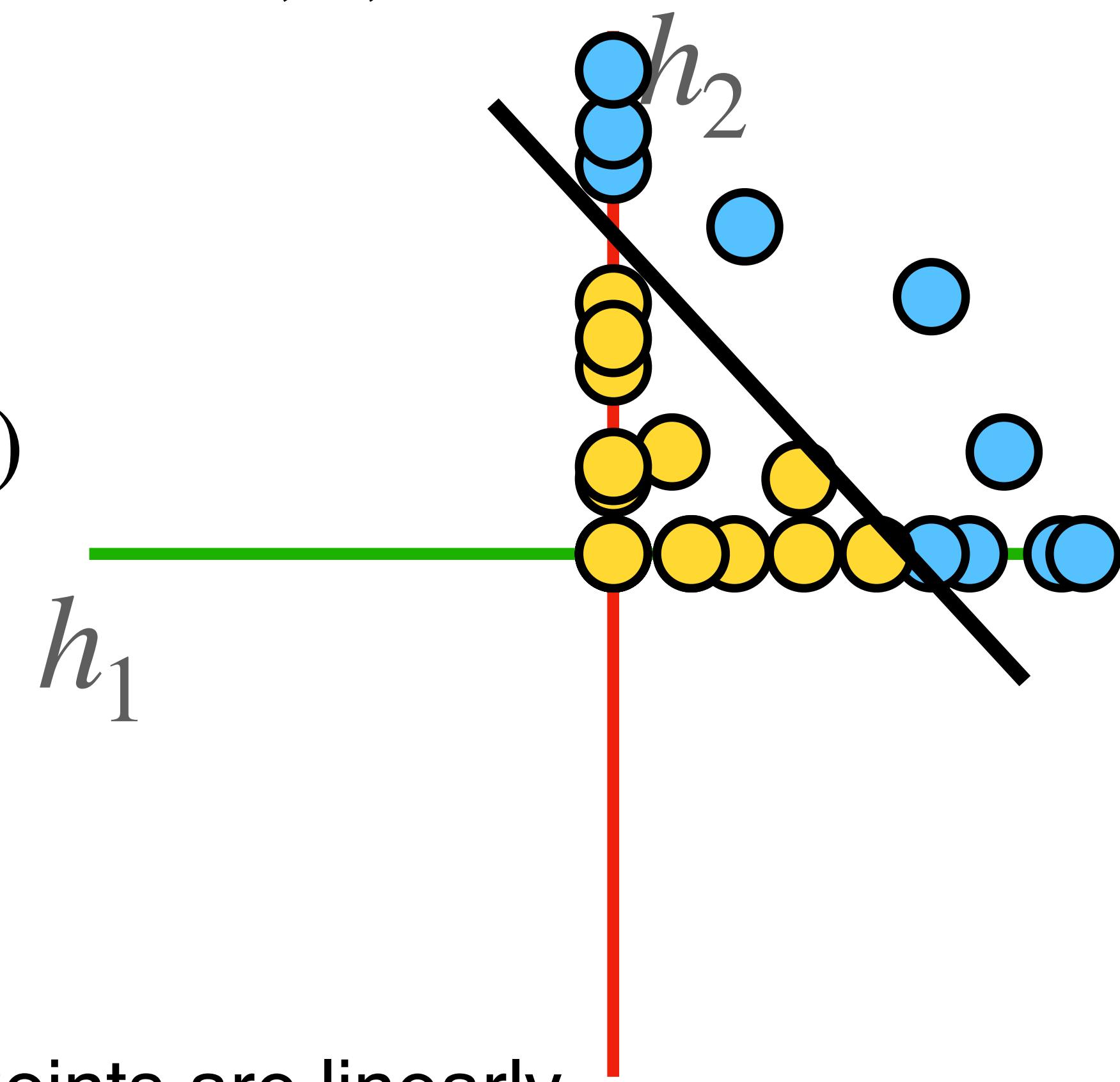
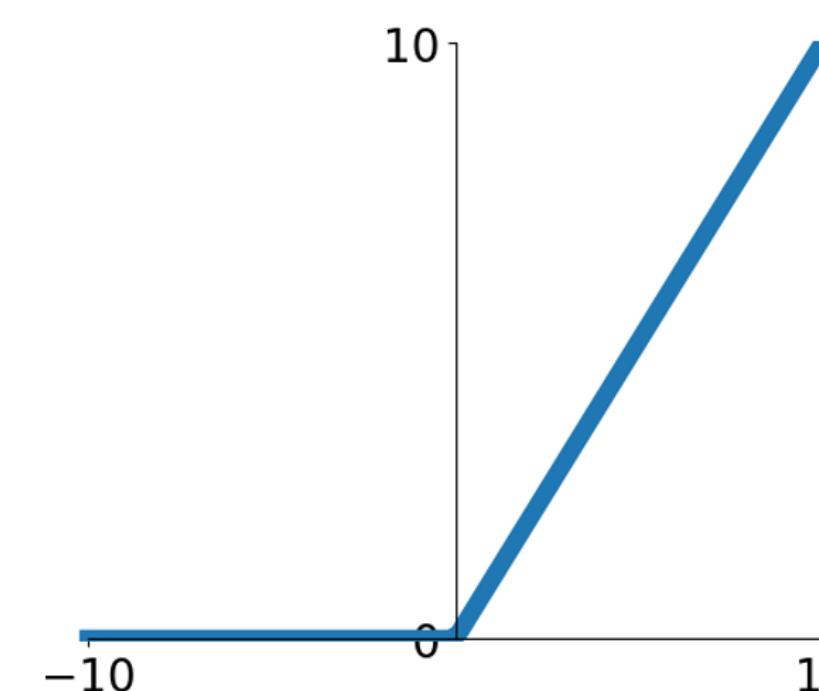
# Space Warping

Points not linearly separable  
in original space



Consider a neural net hidden layer:  $h = \text{ReLU}(Wx + b)$   
 $= \max(0, Wx + b)$  where  $x, b, h$  are each 2-dimensional

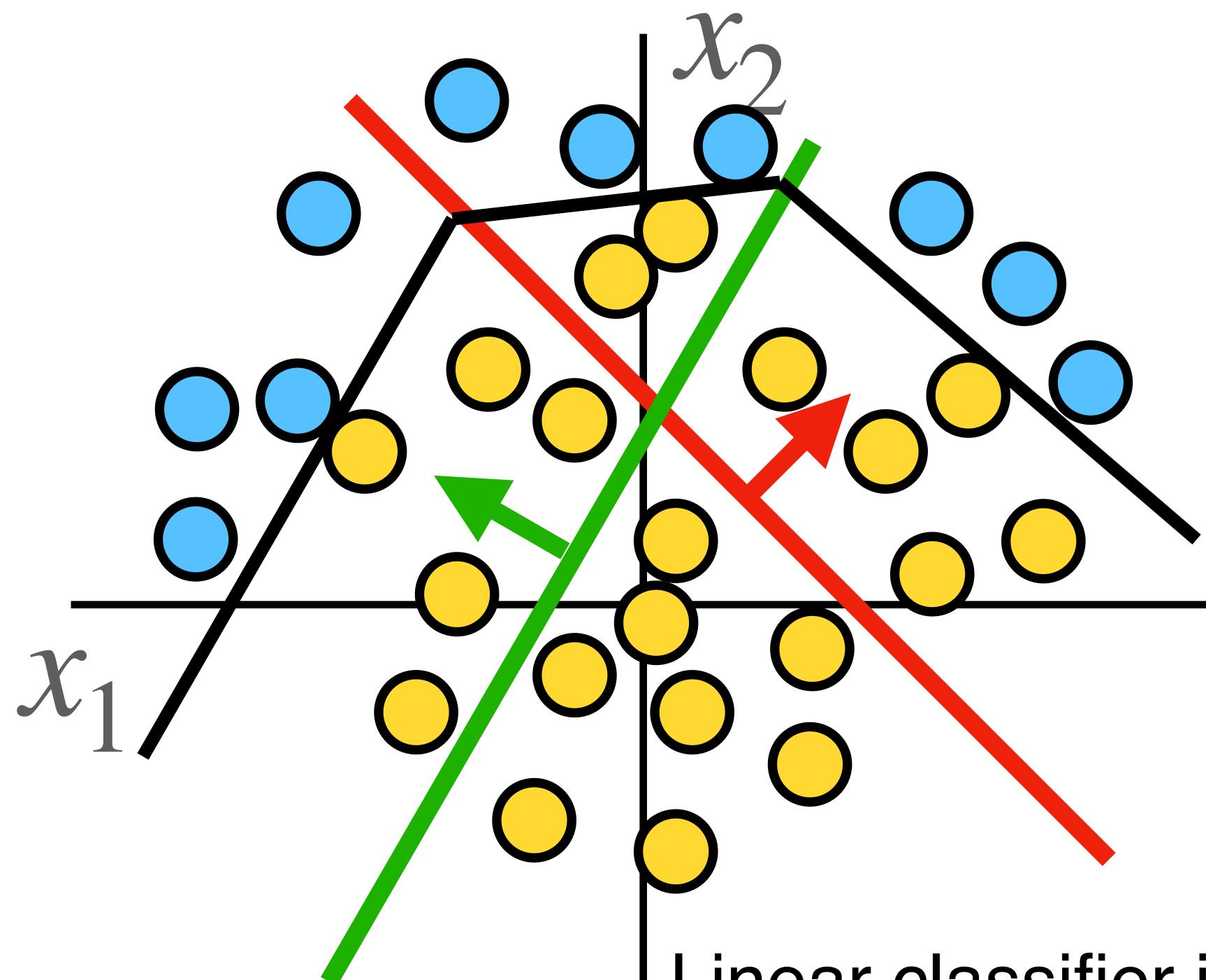
Feature transform:  
 $h = \text{ReLU}(Wx + b)$



Points are linearly  
separable in feature space!

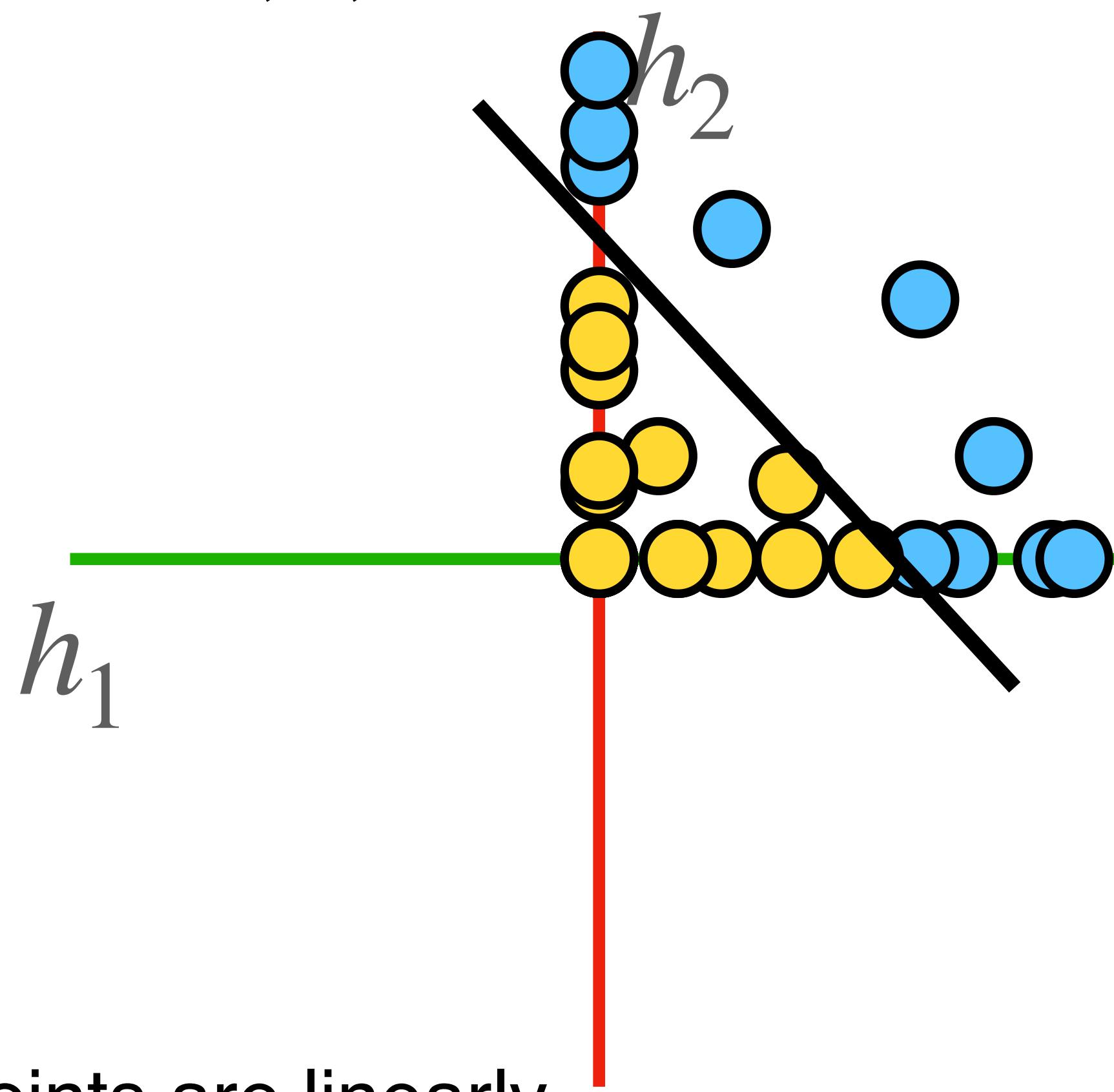
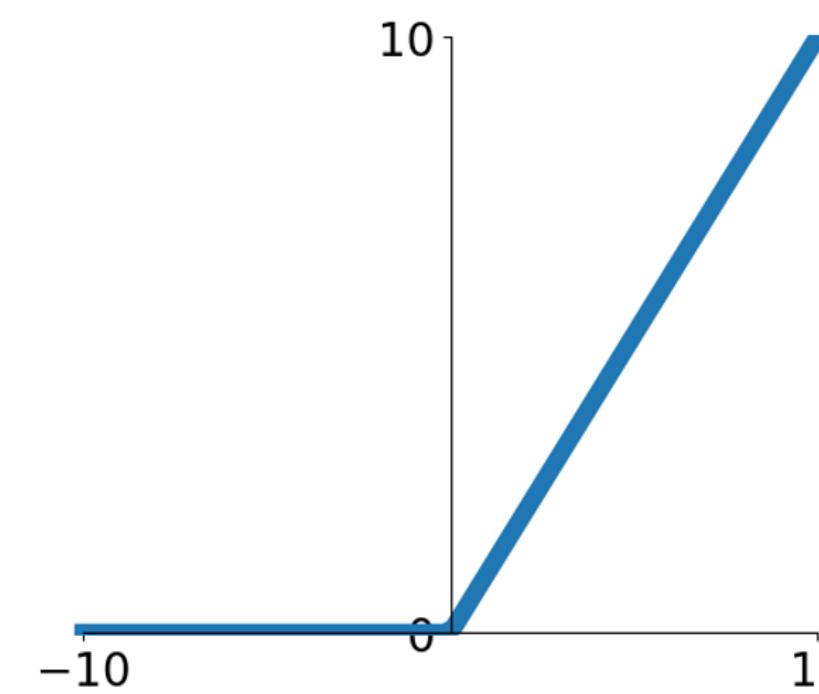
# Space Warping

Points not linearly separable  
in original space



Consider a neural net hidden layer:  $h = \text{ReLU}(Wx + b) = \max(0, Wx + b)$  where  $x, b, h$  are each 2-dimensional

Feature transform:  
 $h = \text{ReLU}(Wx + b)$

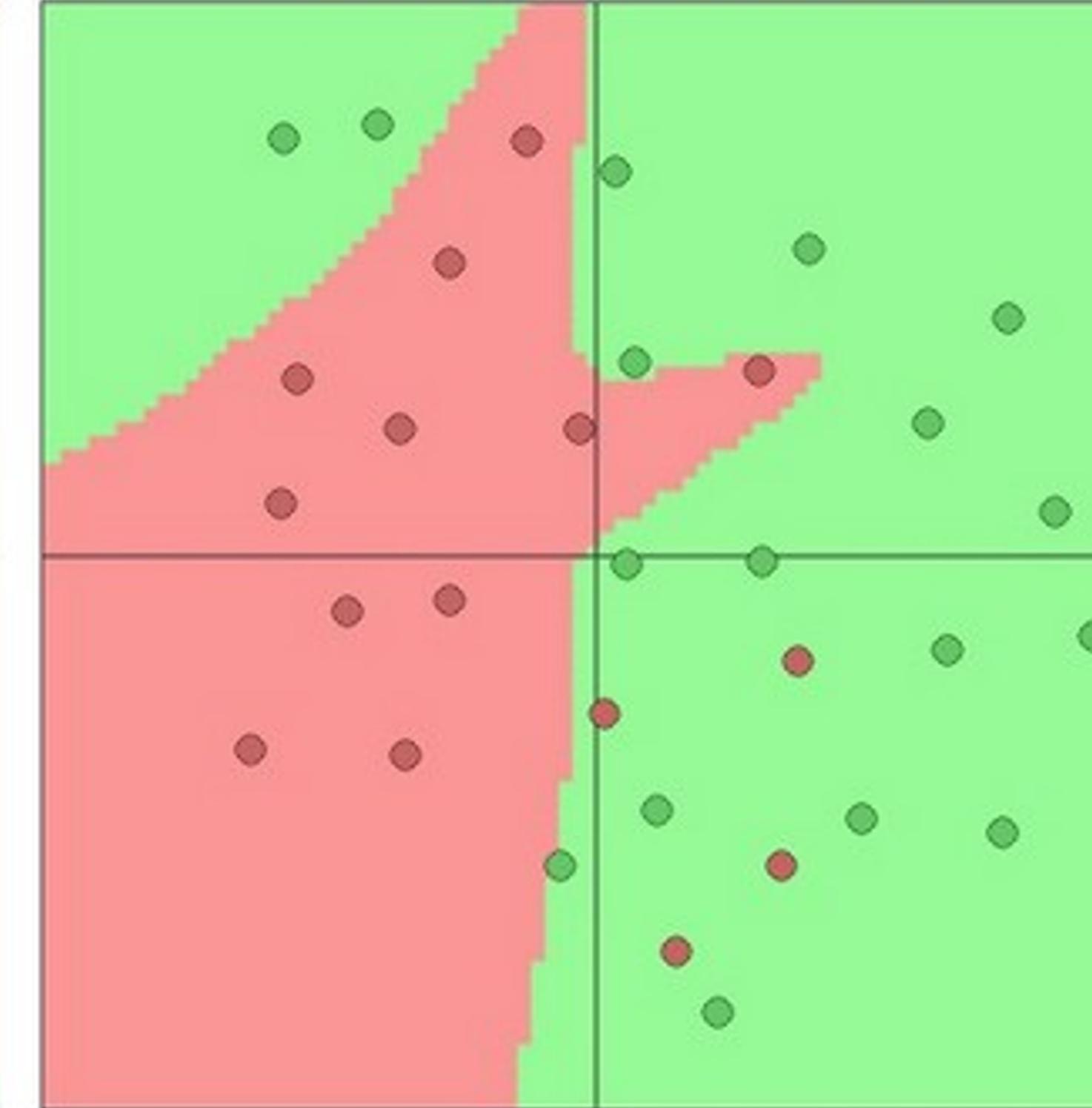


# Setting the number of layers and their sizes

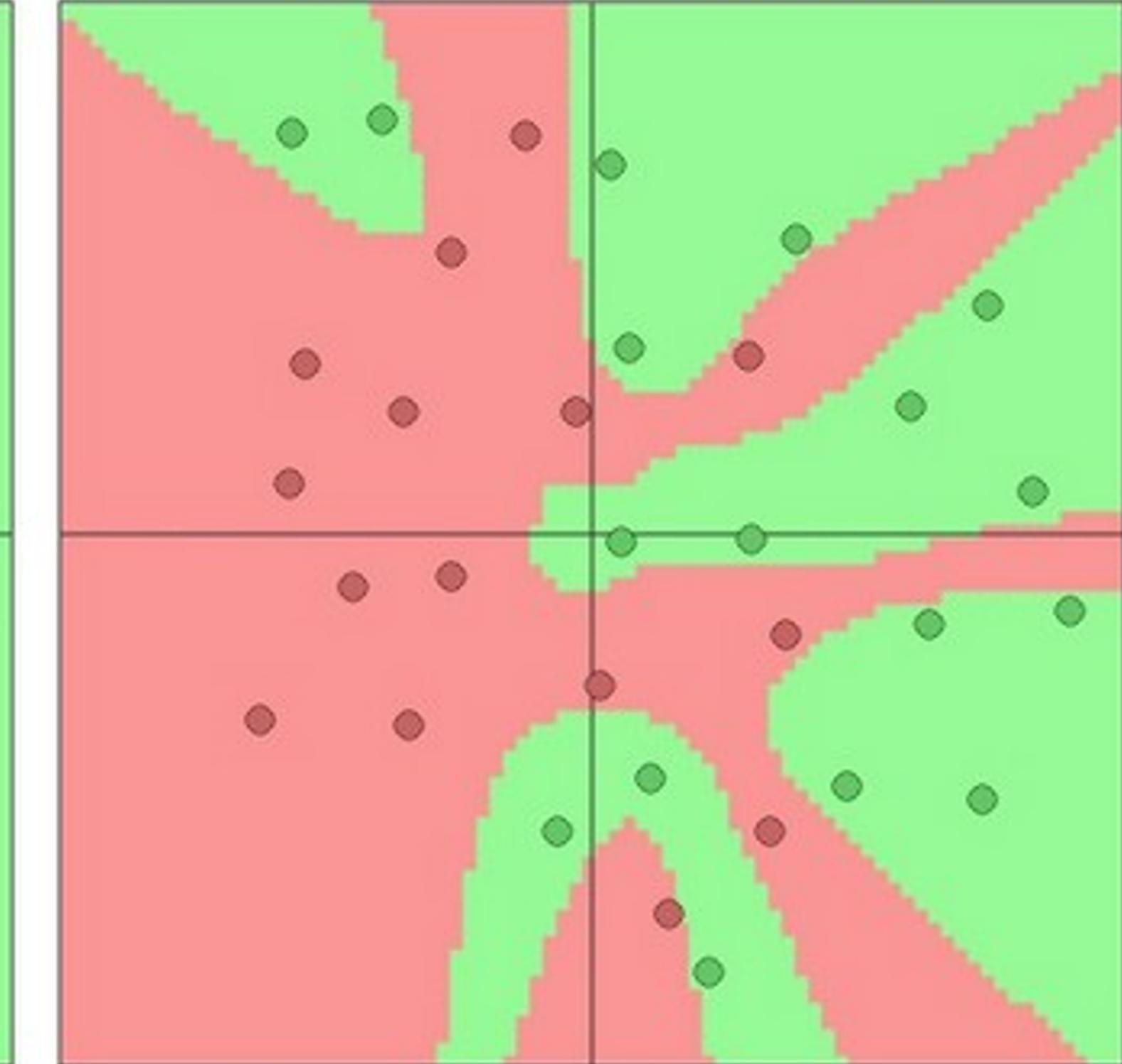
3 hidden units



6 hidden units



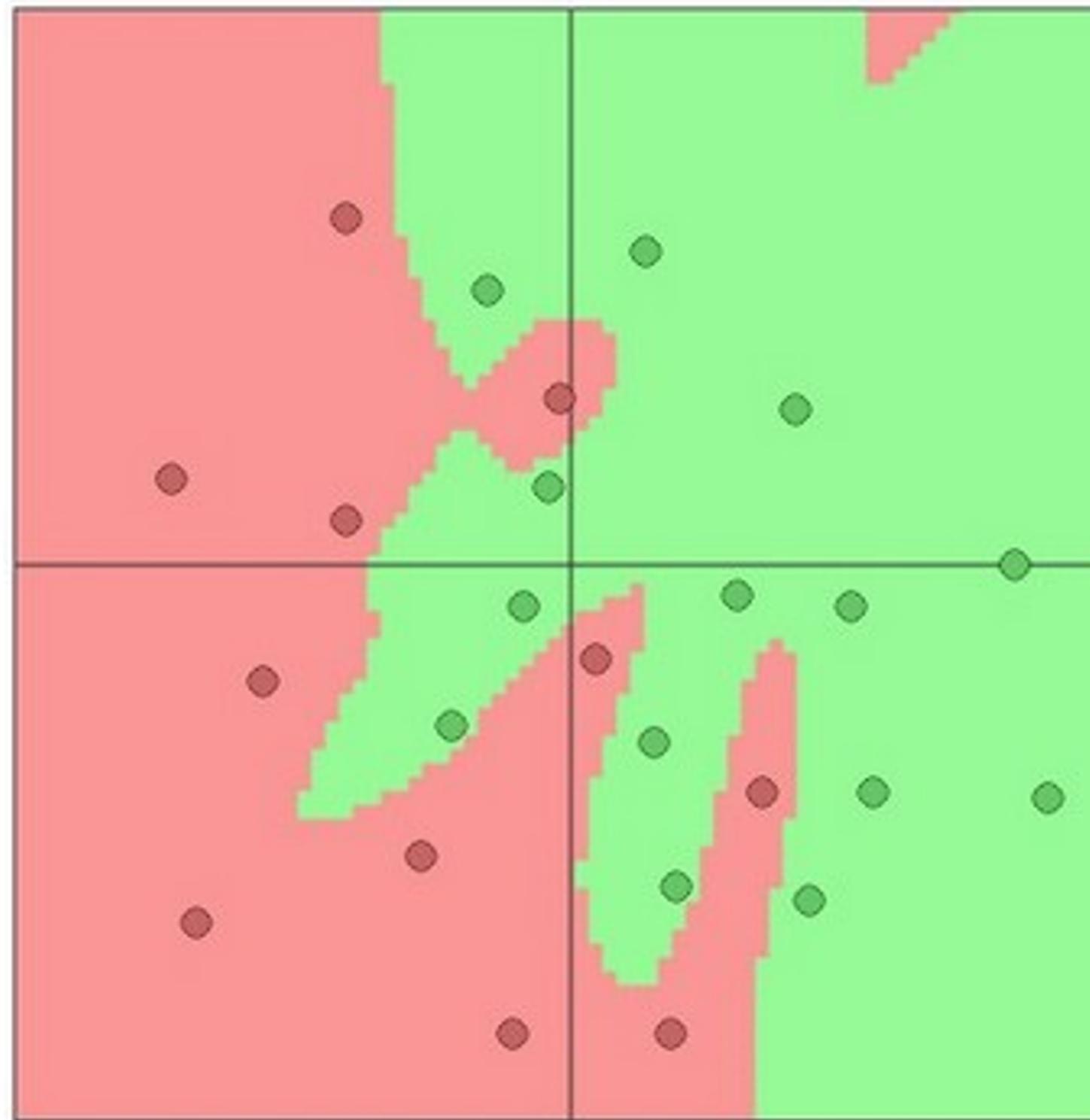
20 hidden units



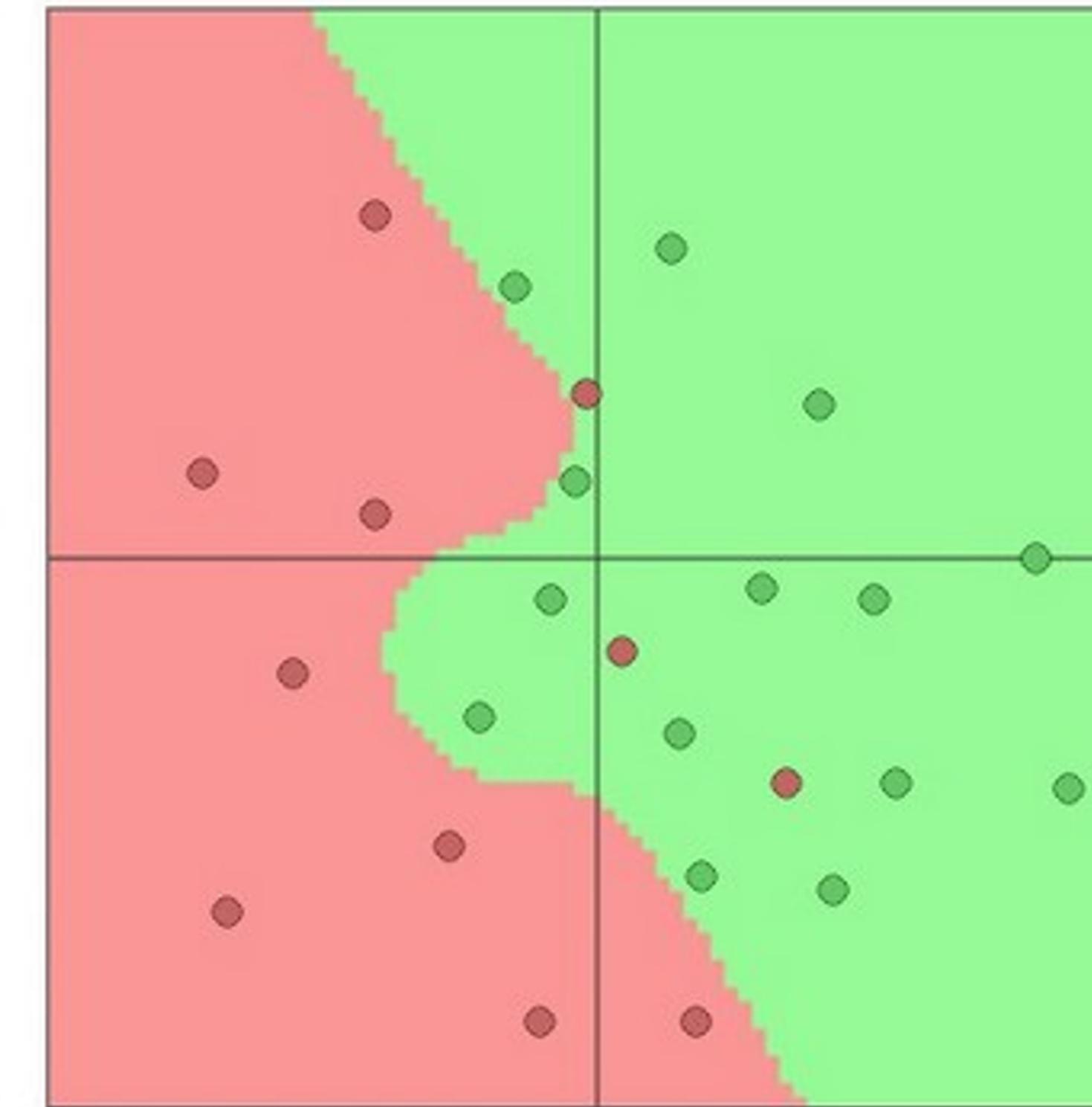
More hidden units = more capacity

# Don't regularize with size; instead use stronger L2

$\lambda = 0.001$



$\lambda = 0.01$



$\lambda = 0.1$



Web demo with ConvNetJS: <https://cs.stanford.edu/people/karpathy/convnetjs/demo/classify2d.html>

# Universal Approximation

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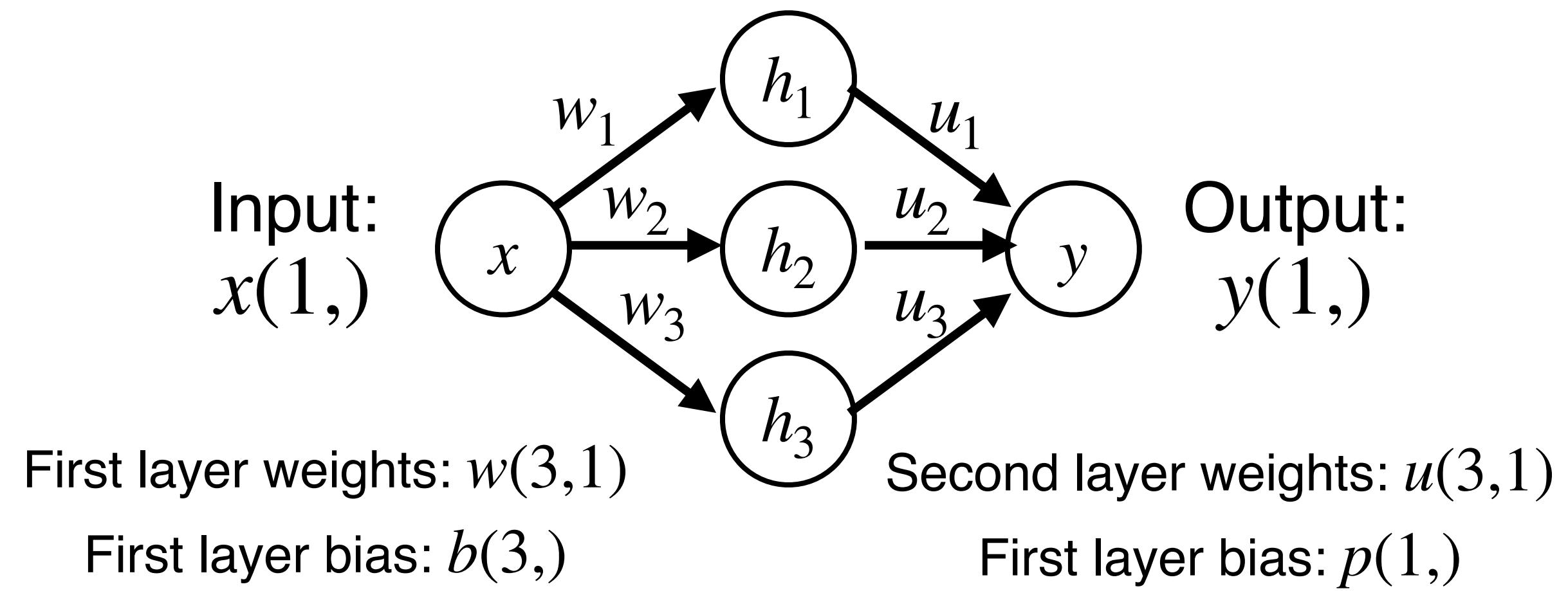
A neural network with one hidden layer can approximate any function  $f: \mathbb{R}^N \rightarrow \mathbb{R}^M$  with arbitrary precision\*

\*Many technical conditions: Only holds on compact subsets of  $\mathbb{R}^N$ ; function must be continuous; need to define "arbitrary precision"; etc.



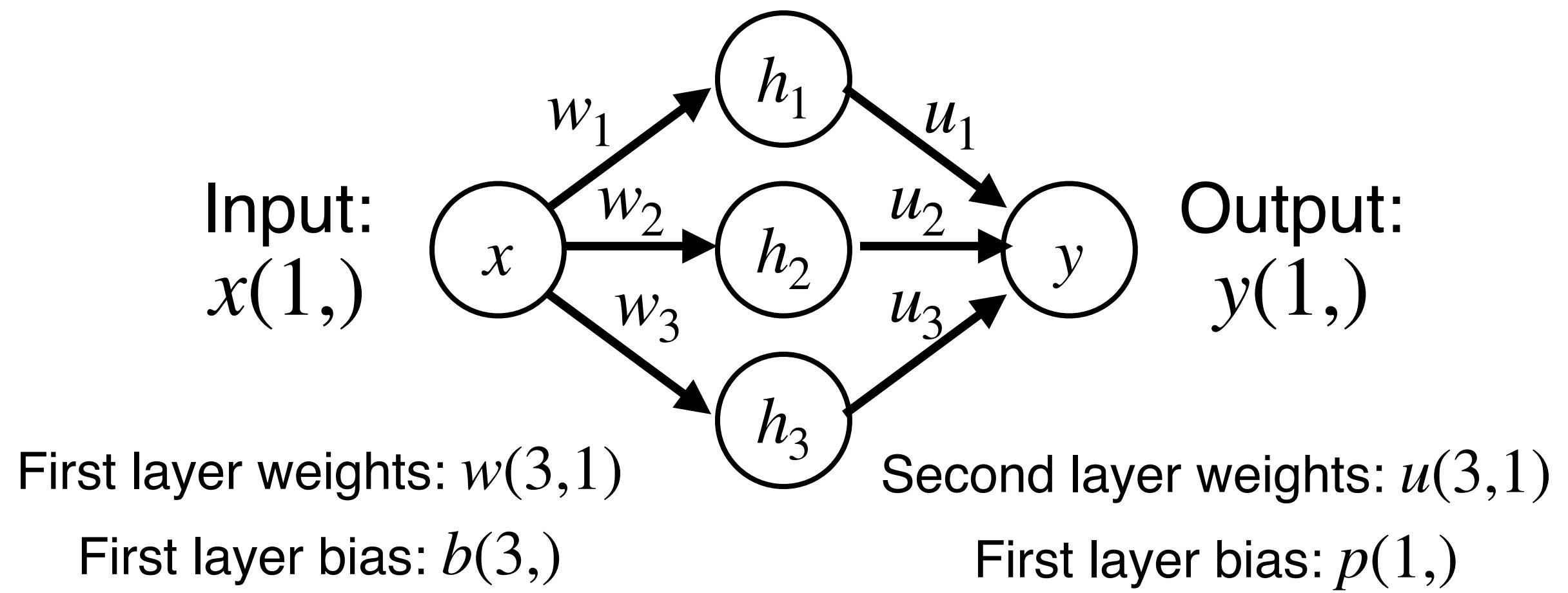
# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



$$h_1 = \max(0, w_1 x + b_1)$$

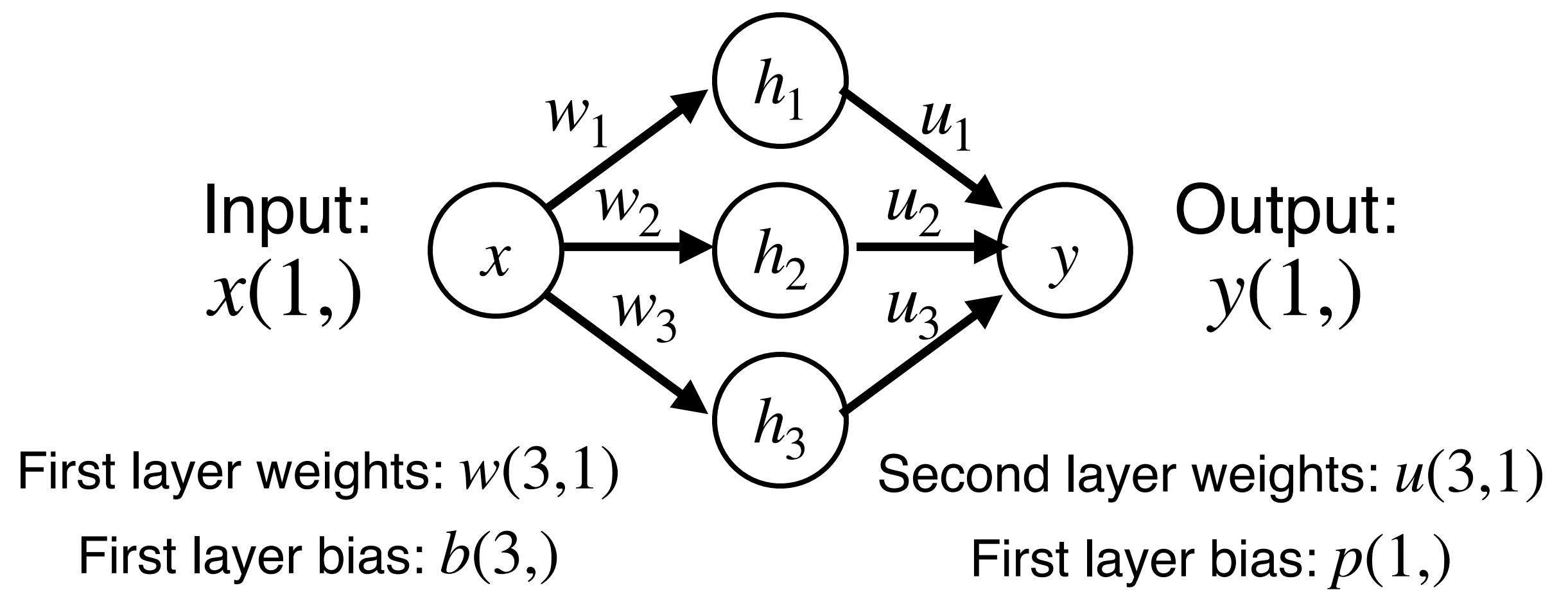
$$h_2 = \max(0, w_2 x + b_2)$$

$$h_3 = \max(0, w_3 x + b_3)$$

$$y = u_1 h_1 + u_2 h_2 + u_3 h_3 + p$$

# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



$$h_1 = \max(0, w_1 x + b_1)$$

$$h_2 = \max(0, w_2 x + b_2)$$

$$h_3 = \max(0, w_3 x + b_3)$$

$$y = u_1 h_1 + u_2 h_2 + u_3 h_3 + p$$

$$y = u_1 \max(0, w_1 x + b_1)$$

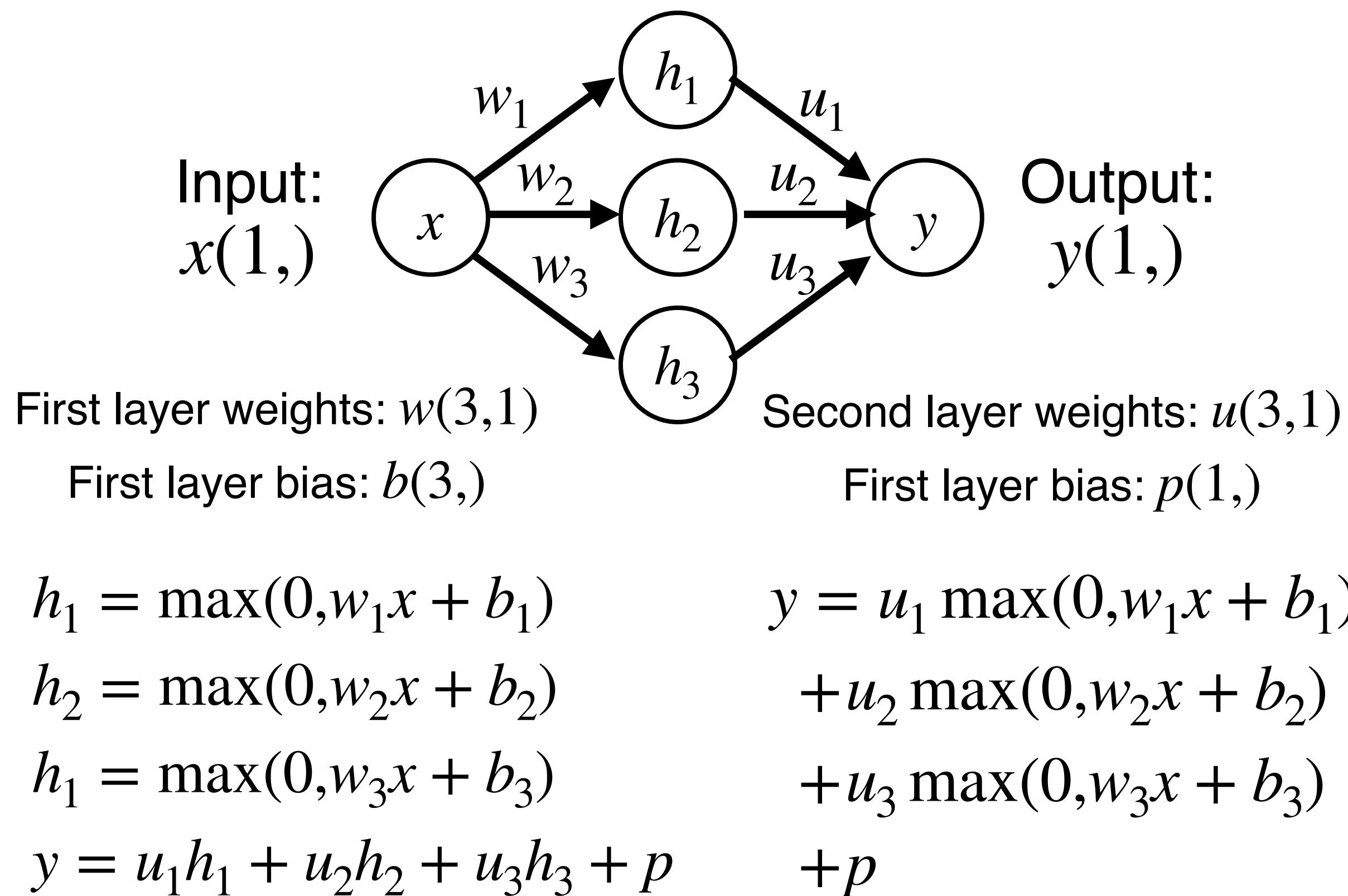
$$+ u_2 \max(0, w_2 x + b_2)$$

$$+ u_3 \max(0, w_3 x + b_3)$$

$$+ p$$

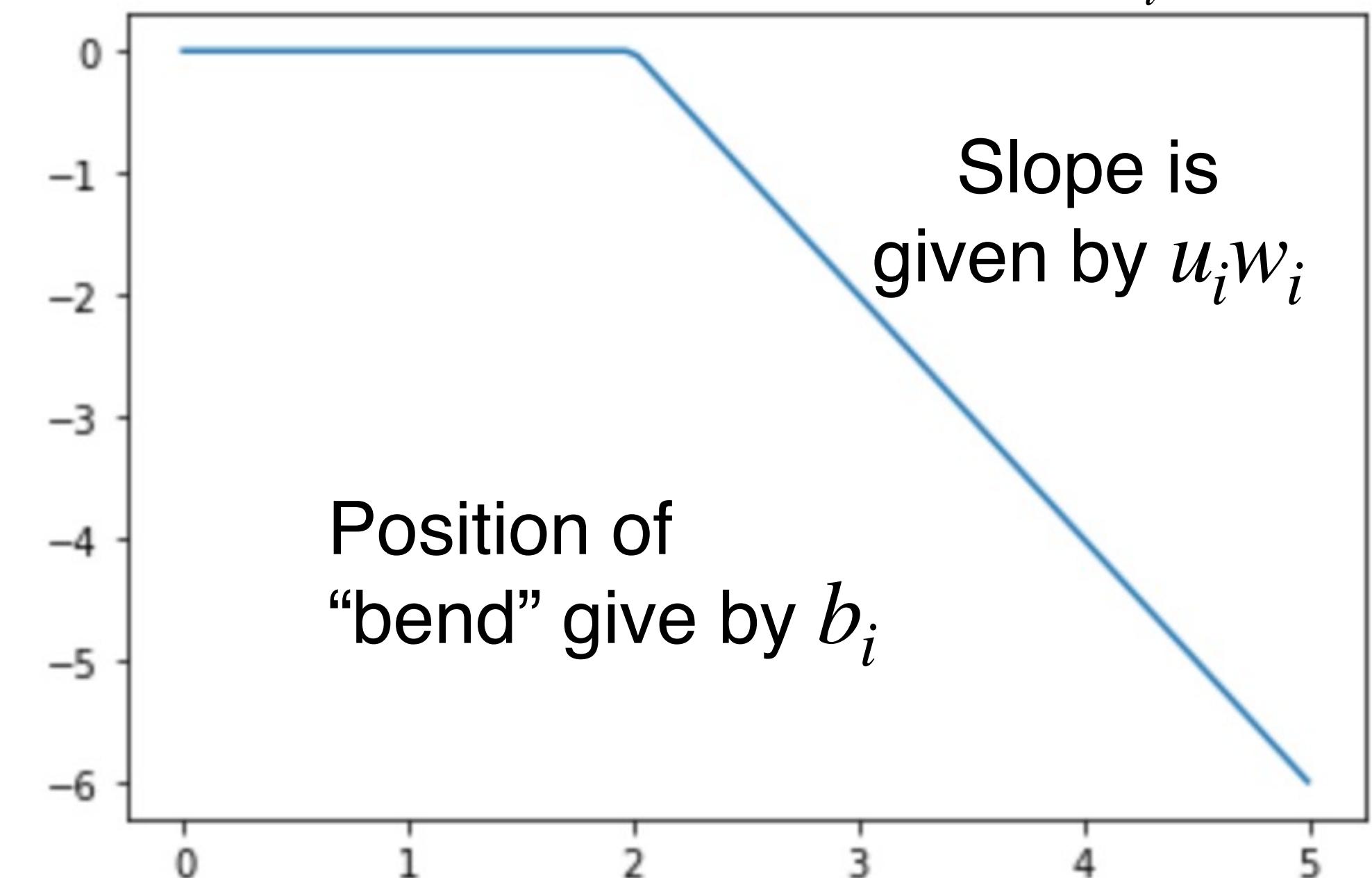
# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



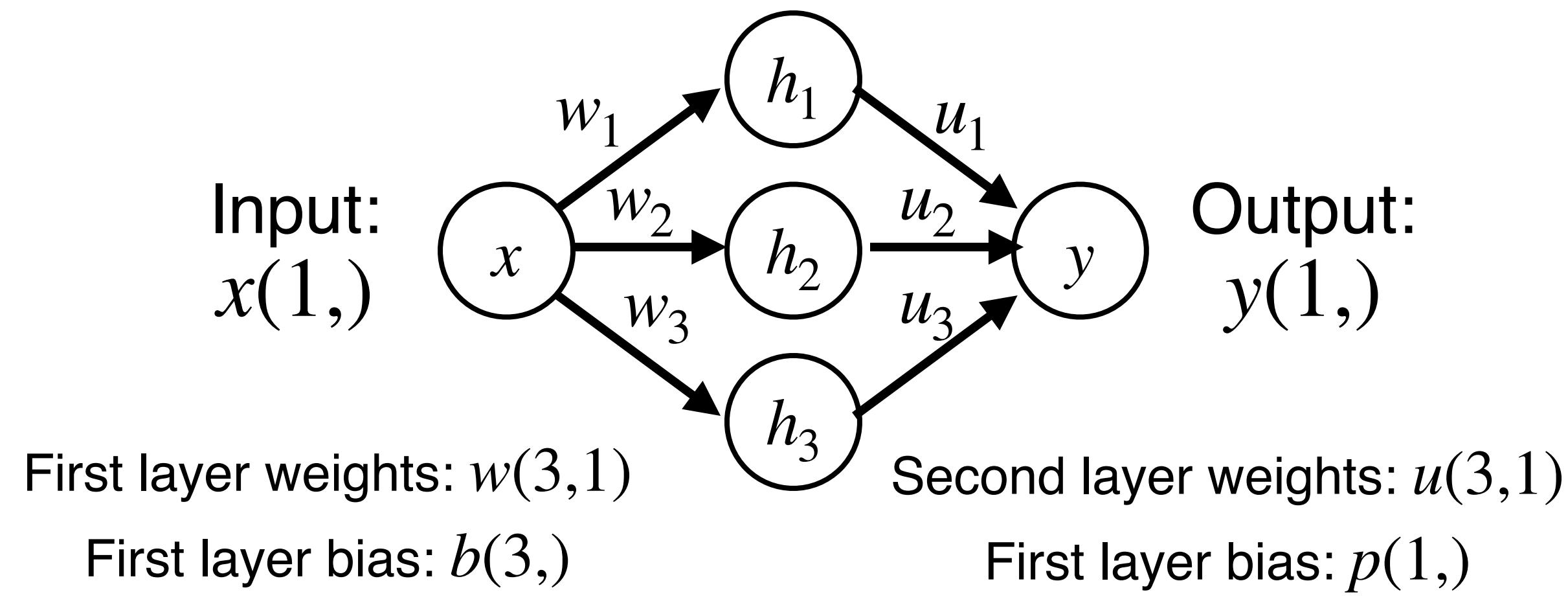
Output is a sum of shifted,  
scaled ReLUs:

Flip left / right based on sign of  $w_i$



# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



$$h_1 = \max(0, w_1 x + b_1)$$

$$h_2 = \max(0, w_2 x + b_2)$$

$$h_3 = \max(0, w_3 x + b_3)$$

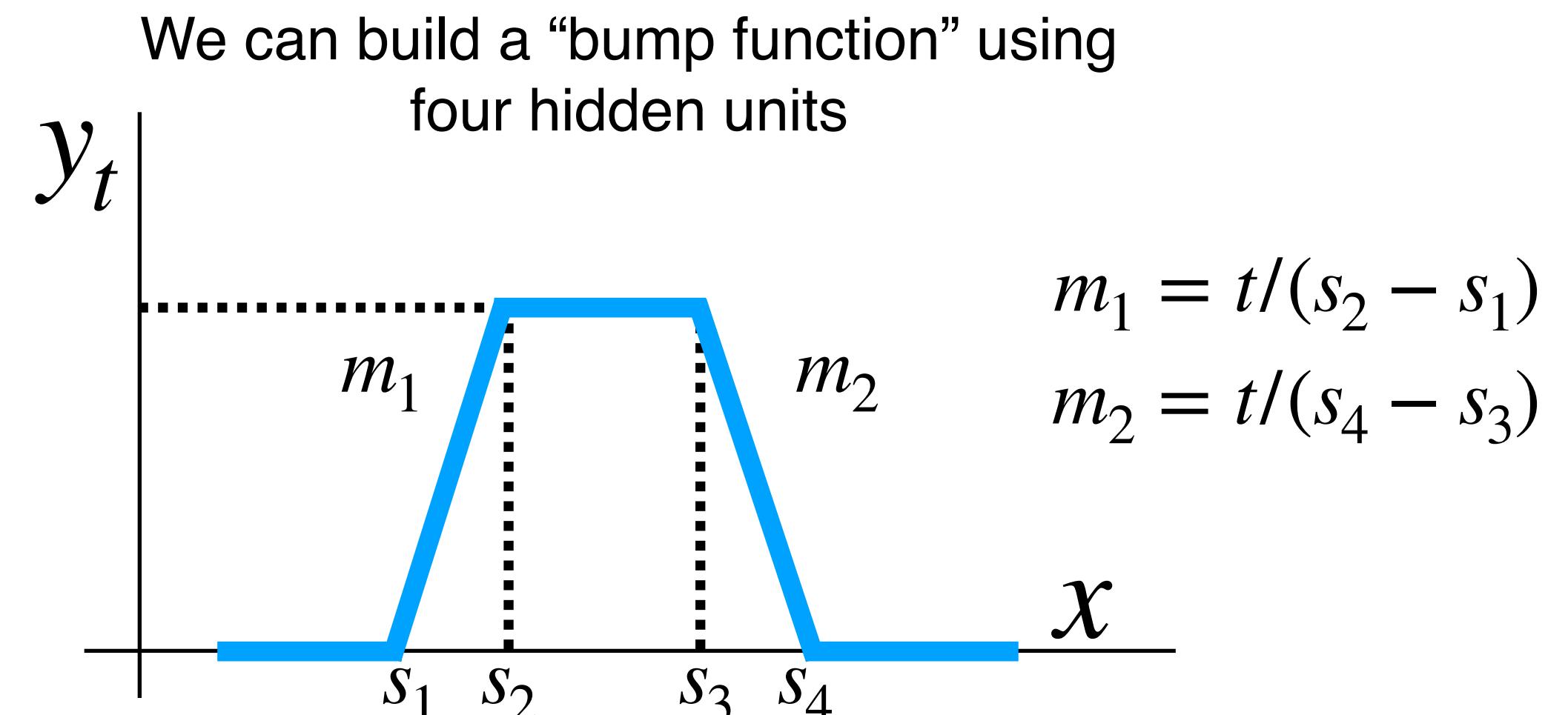
$$y = u_1 h_1 + u_2 h_2 + u_3 h_3 + p$$

$$y = u_1 \max(0, w_1 x + b_1)$$

$$+ u_2 \max(0, w_2 x + b_2)$$

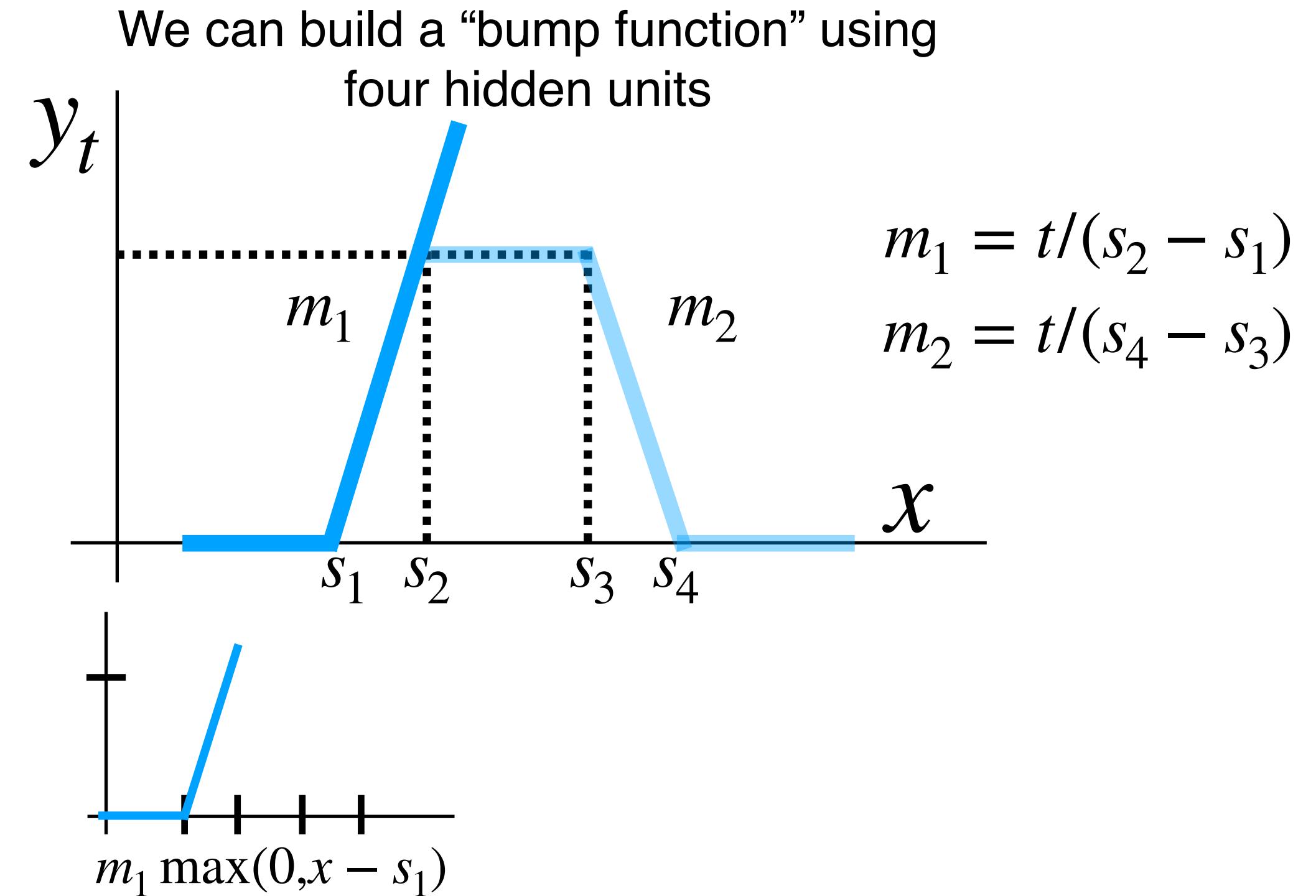
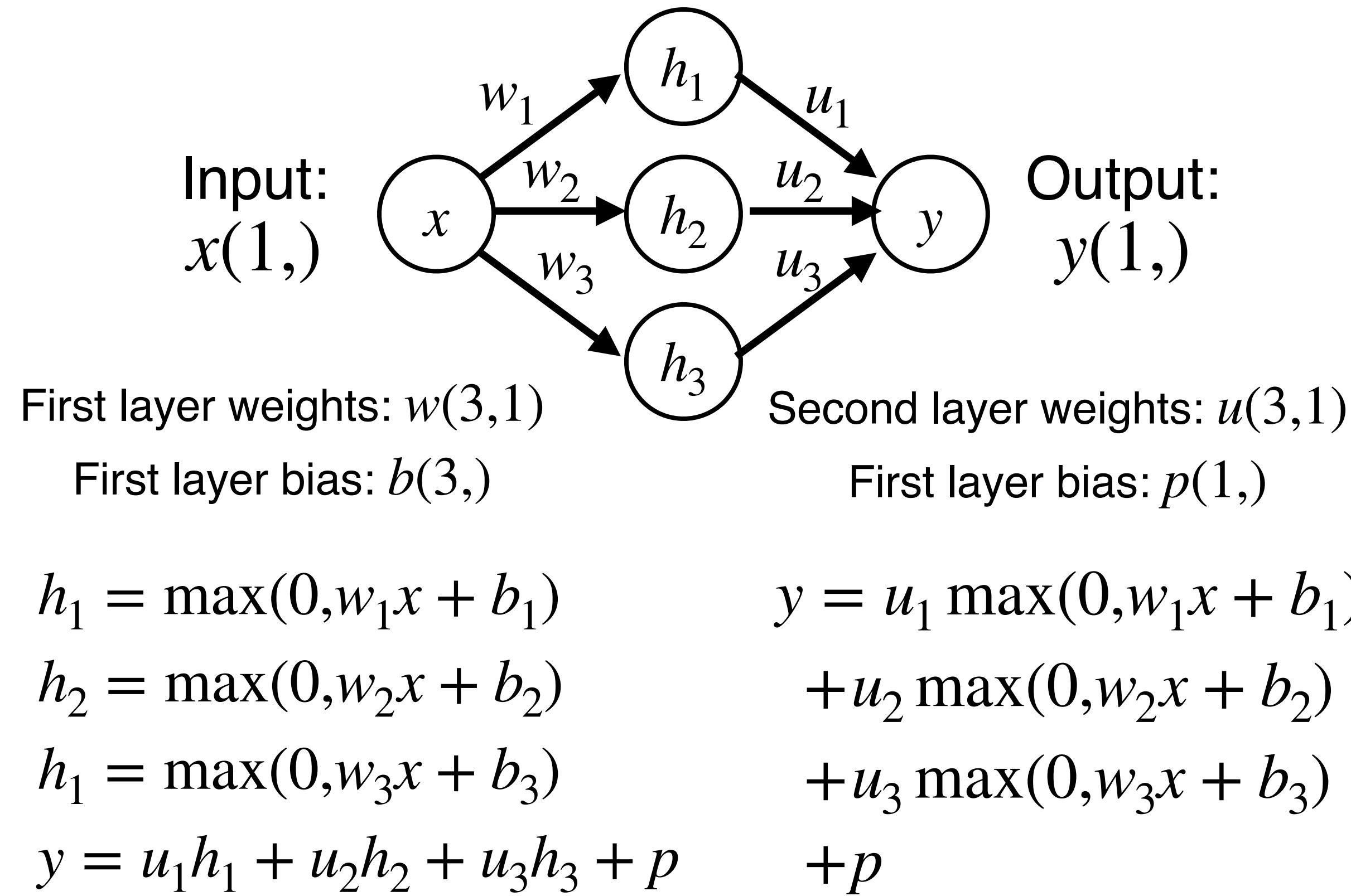
$$+ u_3 \max(0, w_3 x + b_3)$$

$$+ p$$



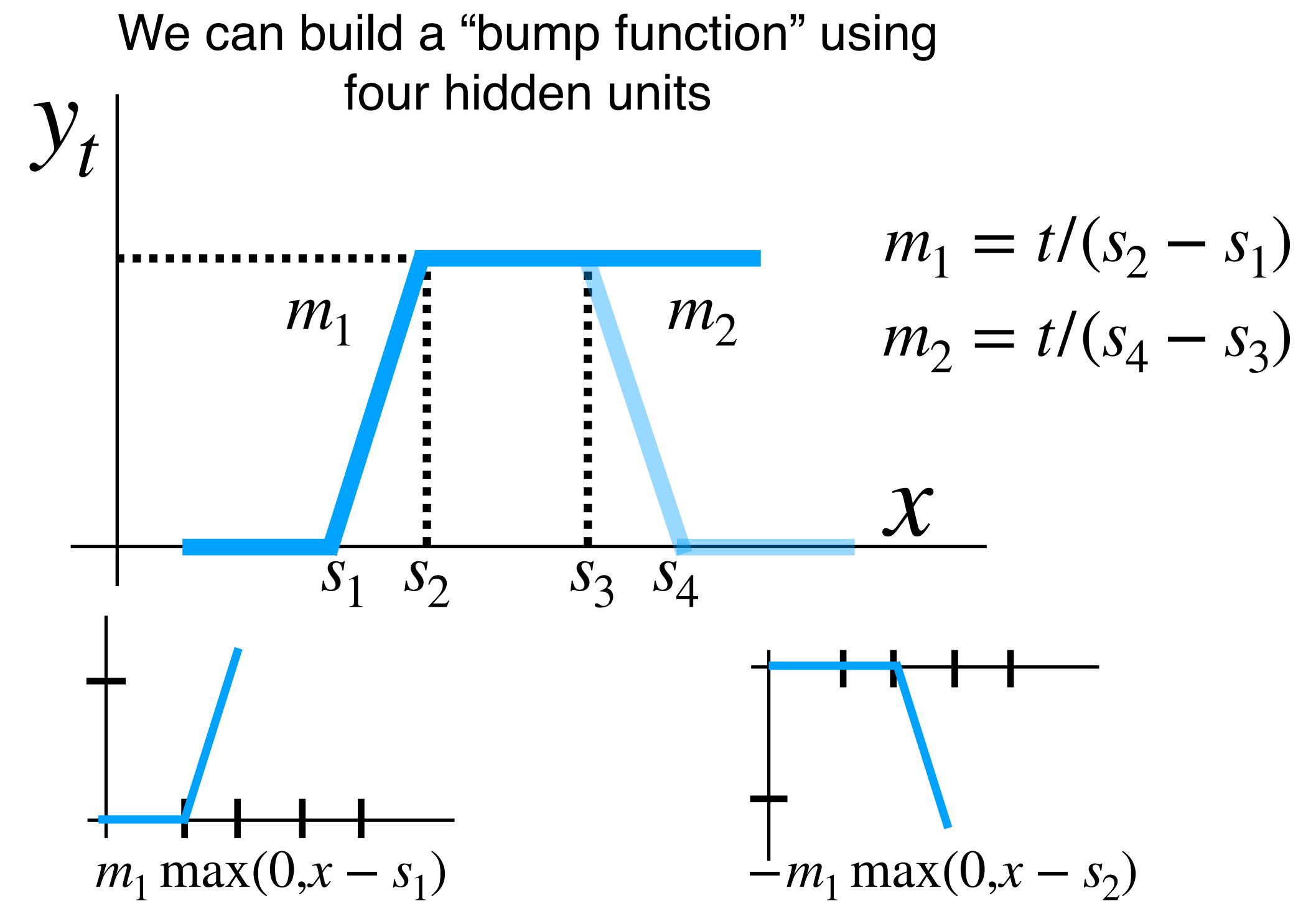
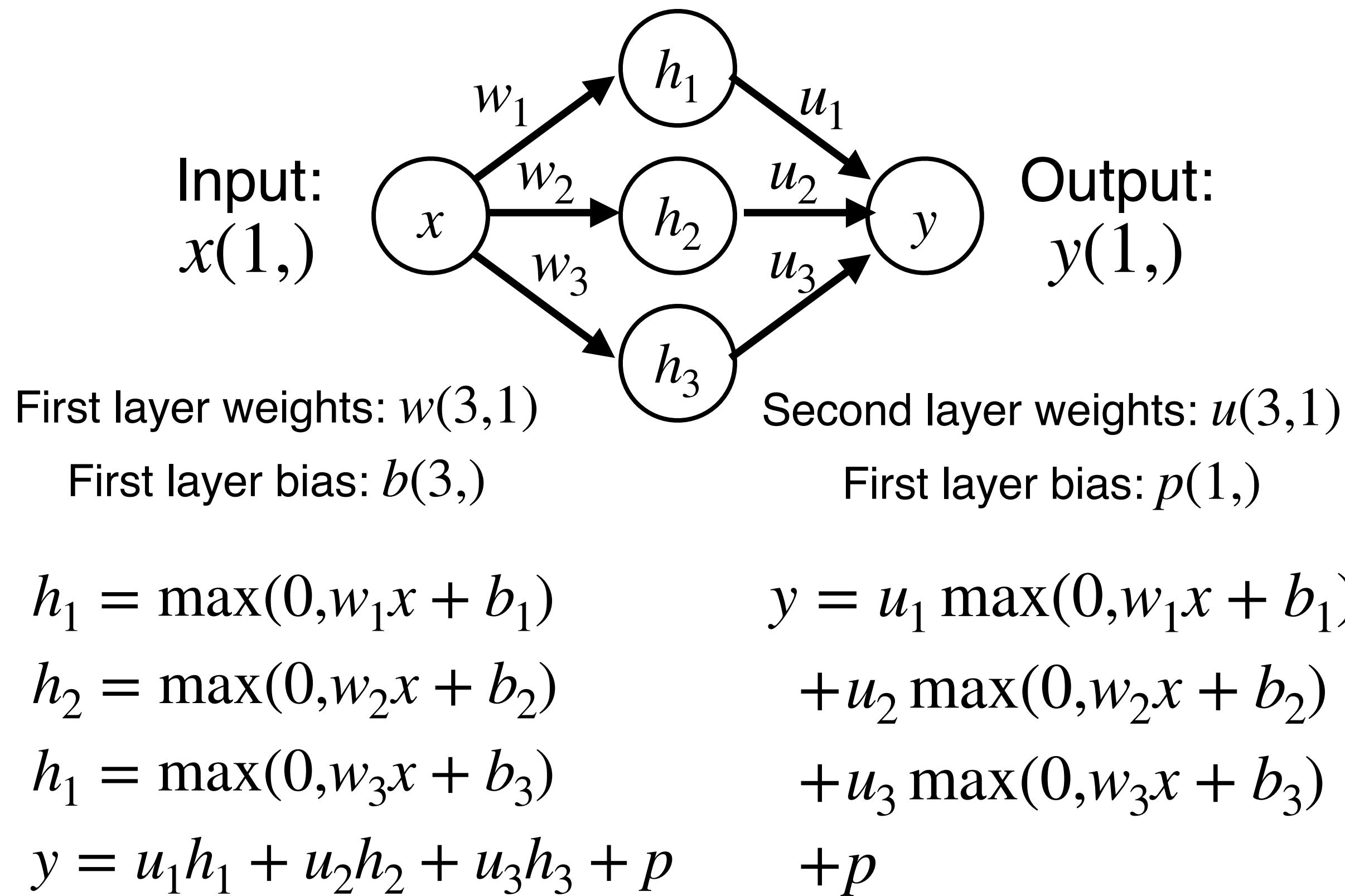
# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



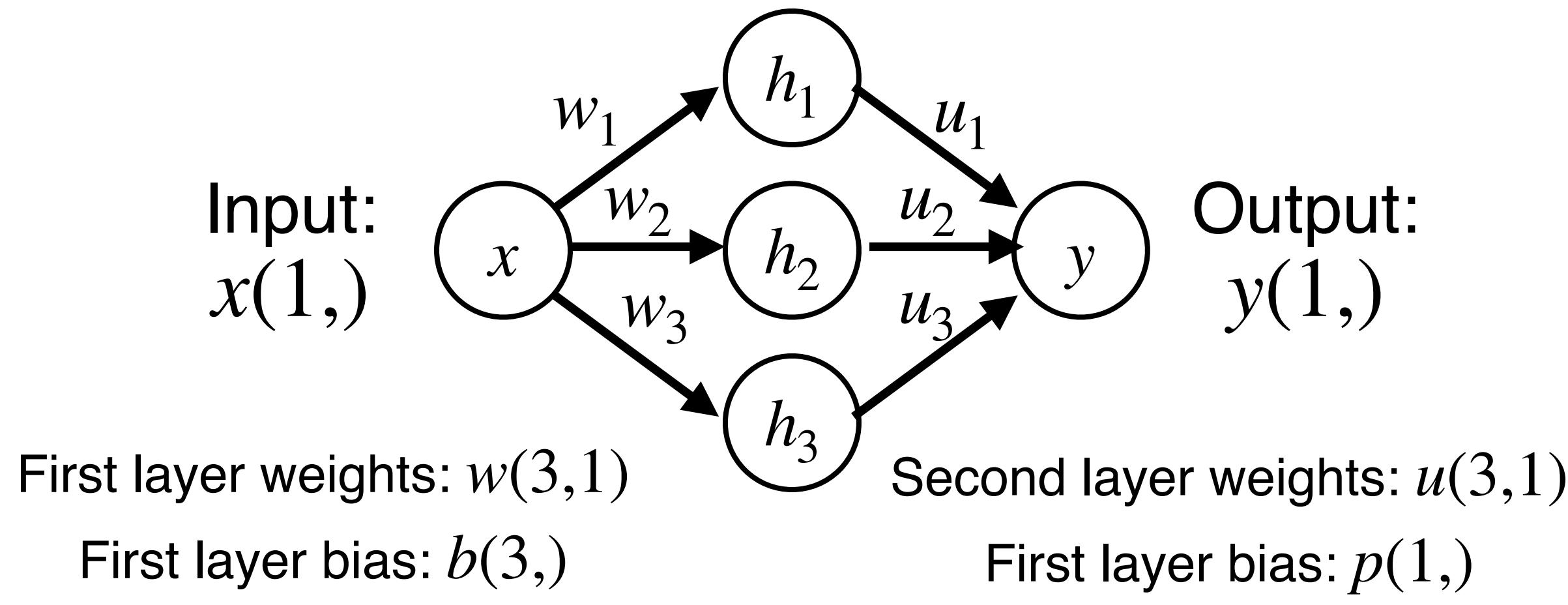
# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



$$h_1 = \max(0, w_1 x + b_1)$$

$$h_2 = \max(0, w_2 x + b_2)$$

$$h_3 = \max(0, w_3 x + b_3)$$

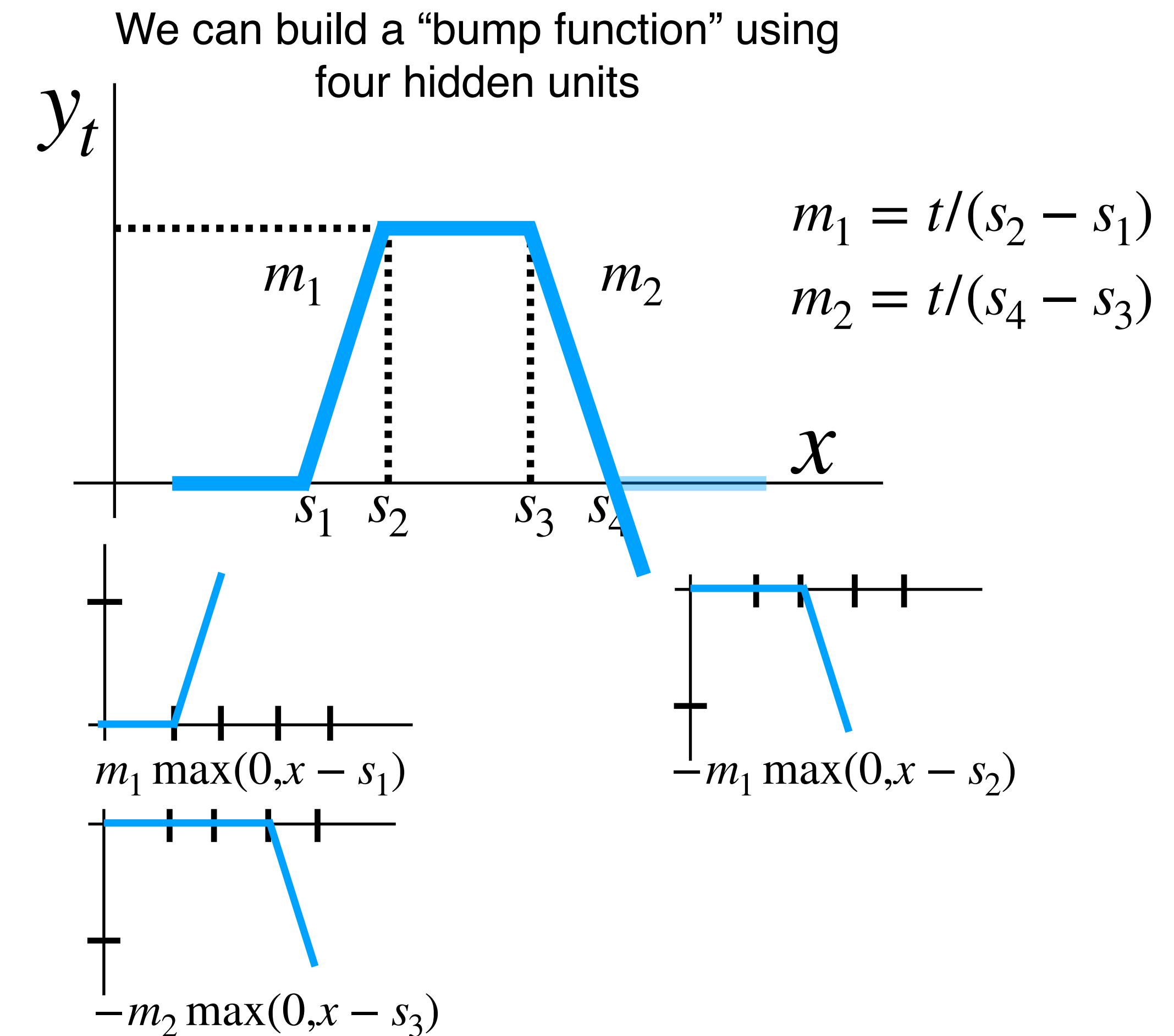
$$y = u_1 h_1 + u_2 h_2 + u_3 h_3 + p$$

$$y = u_1 \max(0, w_1 x + b_1)$$

$$+ u_2 \max(0, w_2 x + b_2)$$

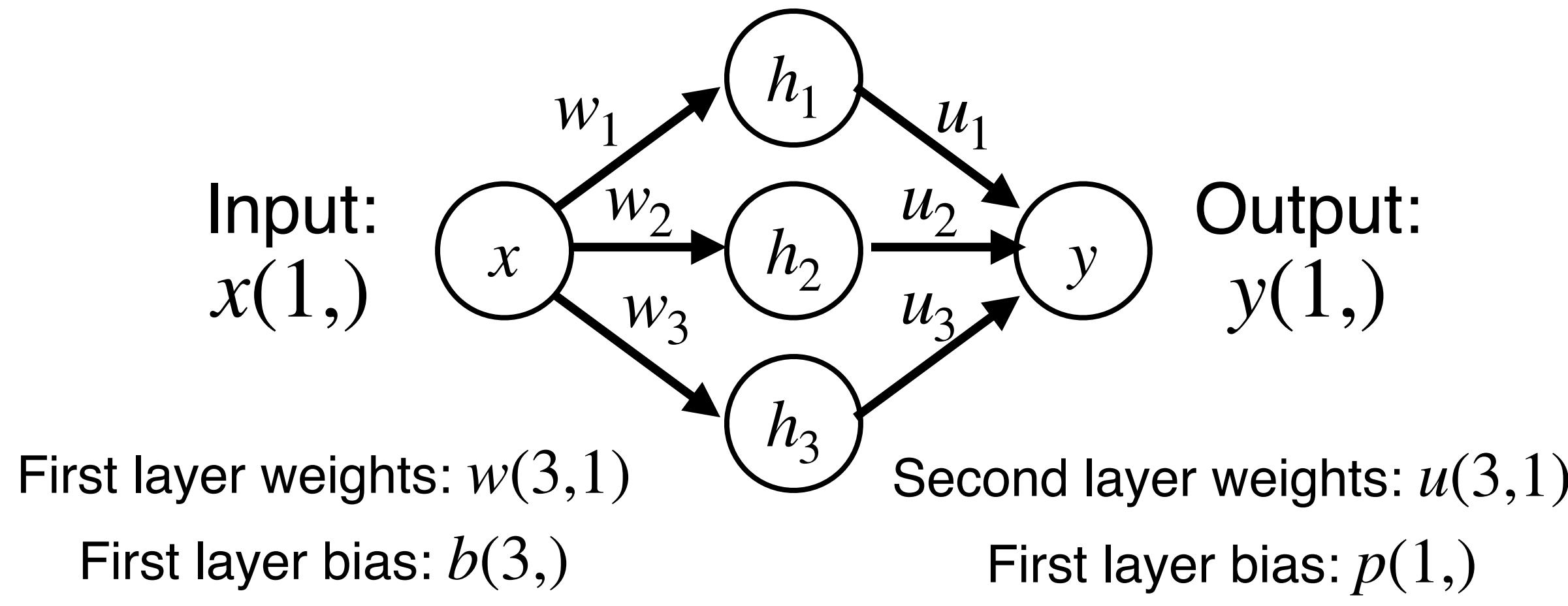
$$+ u_3 \max(0, w_3 x + b_3)$$

$$+ p$$



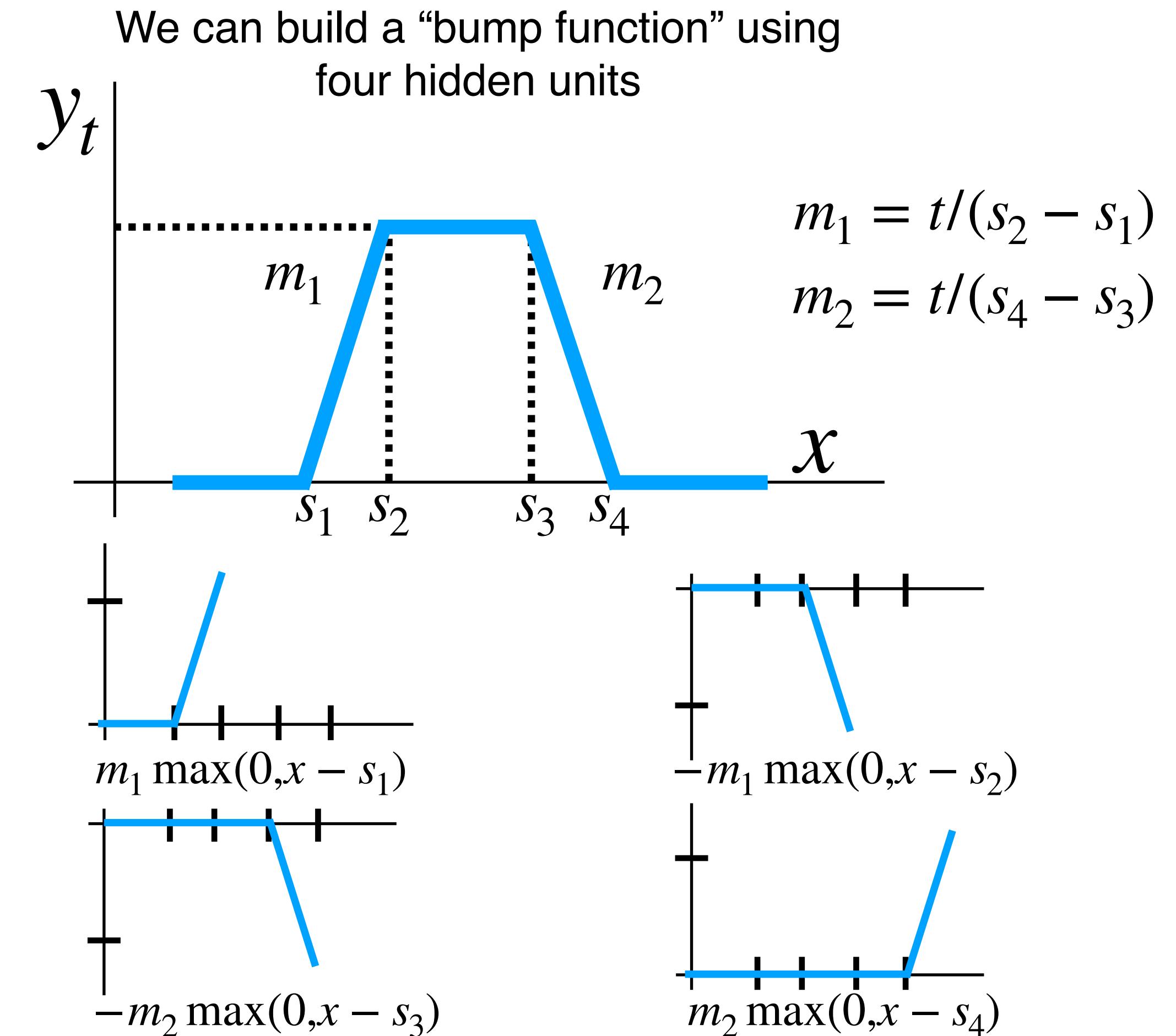
# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



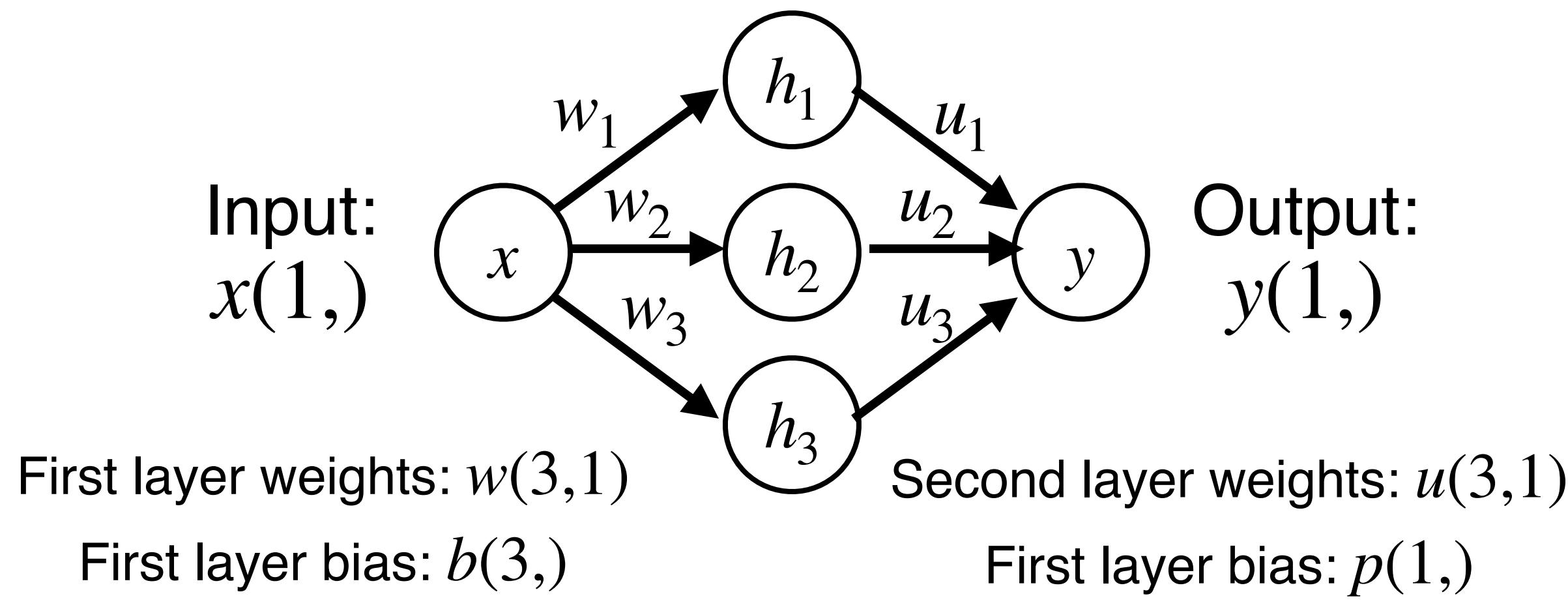
$$\begin{aligned} h_1 &= \max(0, w_1 x + b_1) \\ h_2 &= \max(0, w_2 x + b_2) \\ h_3 &= \max(0, w_3 x + b_3) \\ y &= u_1 h_1 + u_2 h_2 + u_3 h_3 + p \end{aligned}$$

$$\begin{aligned} y &= u_1 \max(0, w_1 x + b_1) \\ &\quad + u_2 \max(0, w_2 x + b_2) \\ &\quad + u_3 \max(0, w_3 x + b_3) \\ &\quad + p \end{aligned}$$



# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



$$h_1 = \max(0, w_1 x + b_1)$$

$$h_2 = \max(0, w_2 x + b_2)$$

$$h_3 = \max(0, w_3 x + b_3)$$

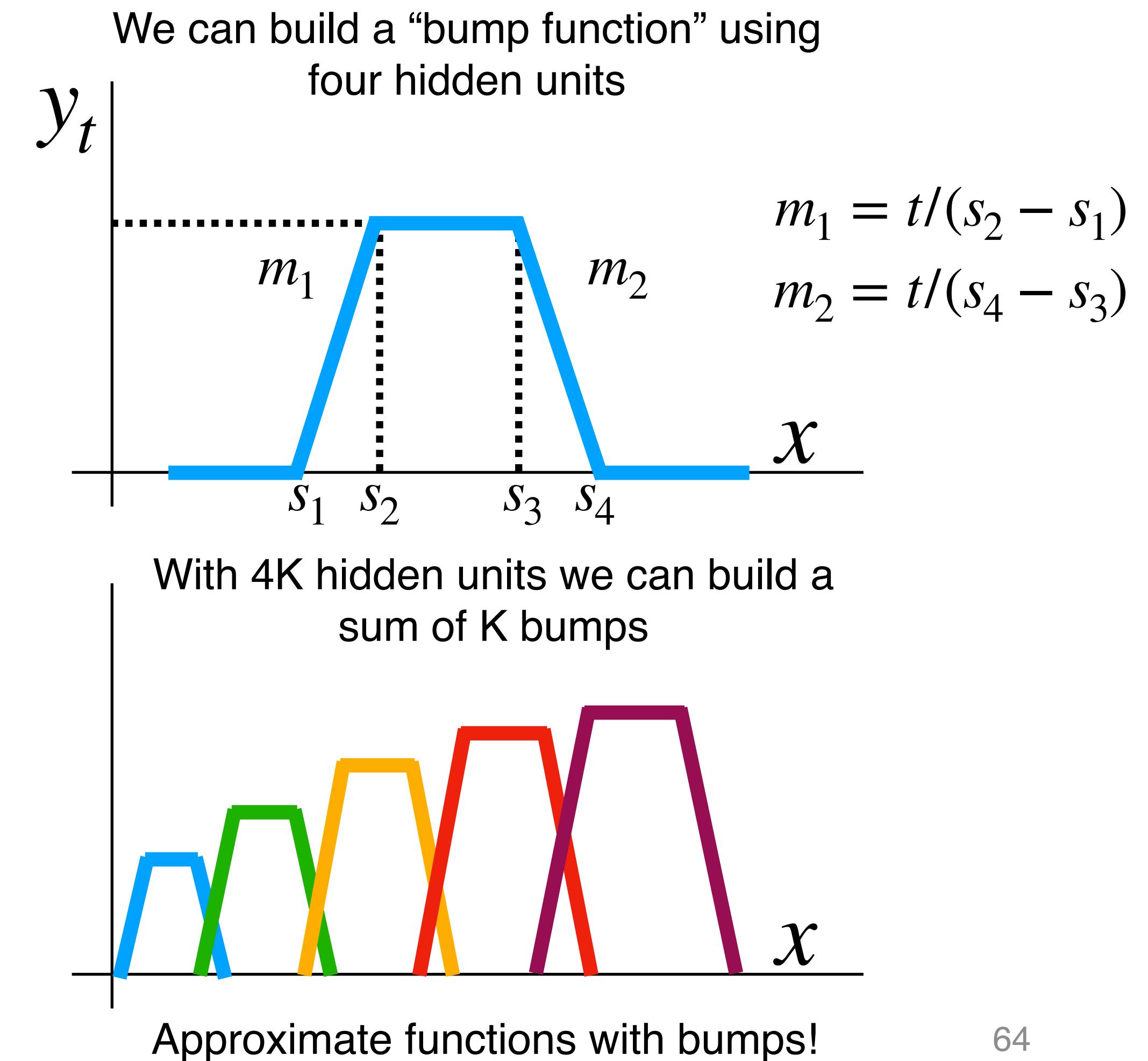
$$y = u_1 h_1 + u_2 h_2 + u_3 h_3 + p$$

$$y = u_1 \max(0, w_1 x + b_1)$$

$$+ u_2 \max(0, w_2 x + b_2)$$

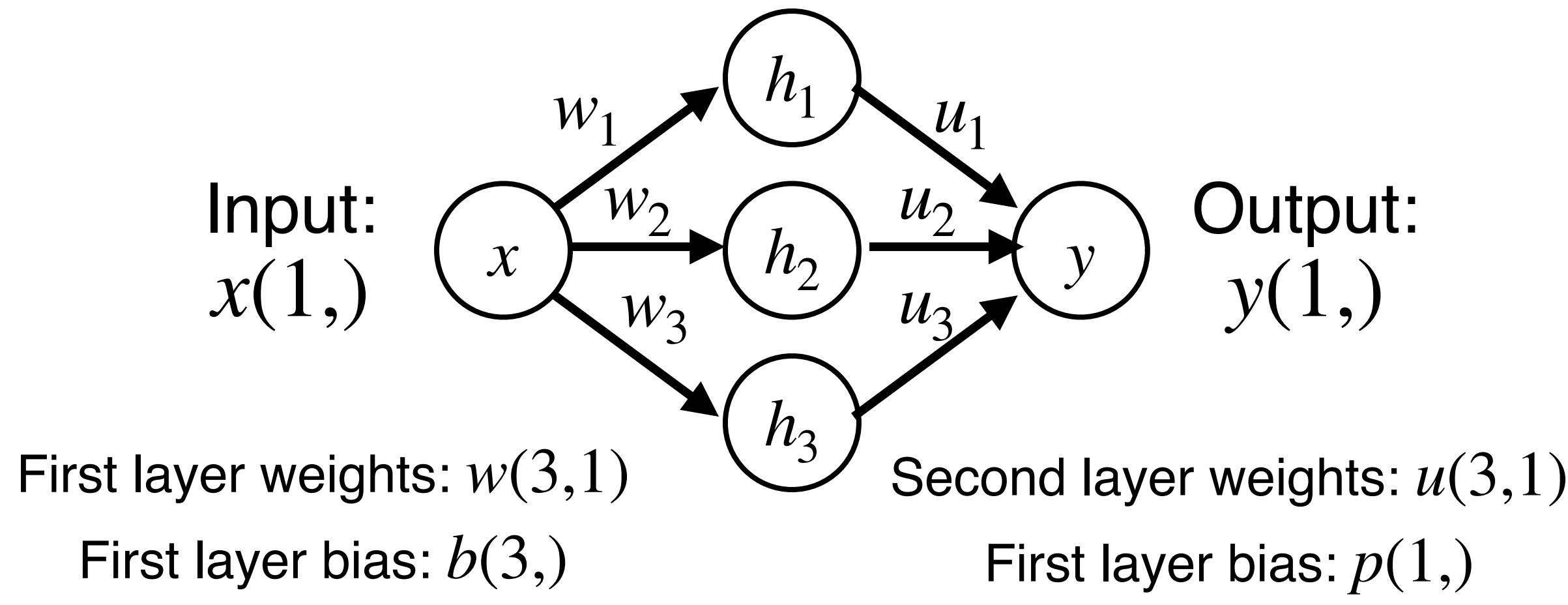
$$+ u_3 \max(0, w_3 x + b_3)$$

$$+ p$$



# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



$$h_1 = \max(0, w_1 x + b_1)$$

$$h_2 = \max(0, w_2 x + b_2)$$

$$h_3 = \max(0, w_3 x + b_3)$$

$$y = u_1 h_1 + u_2 h_2 + u_3 h_3 + p$$

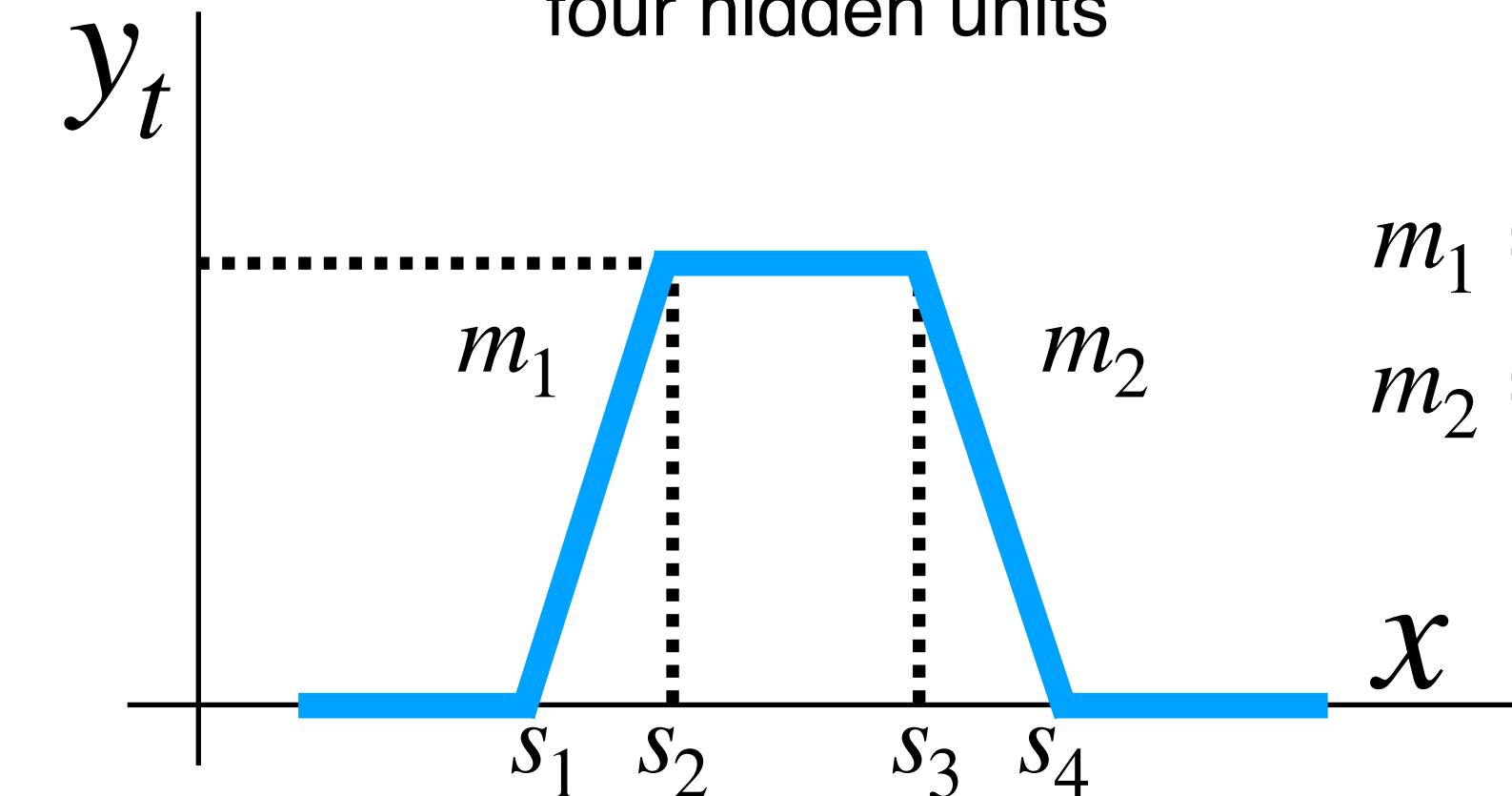
$$y = u_1 \max(0, w_1 x + b_1)$$

$$+ u_2 \max(0, w_2 x + b_2)$$

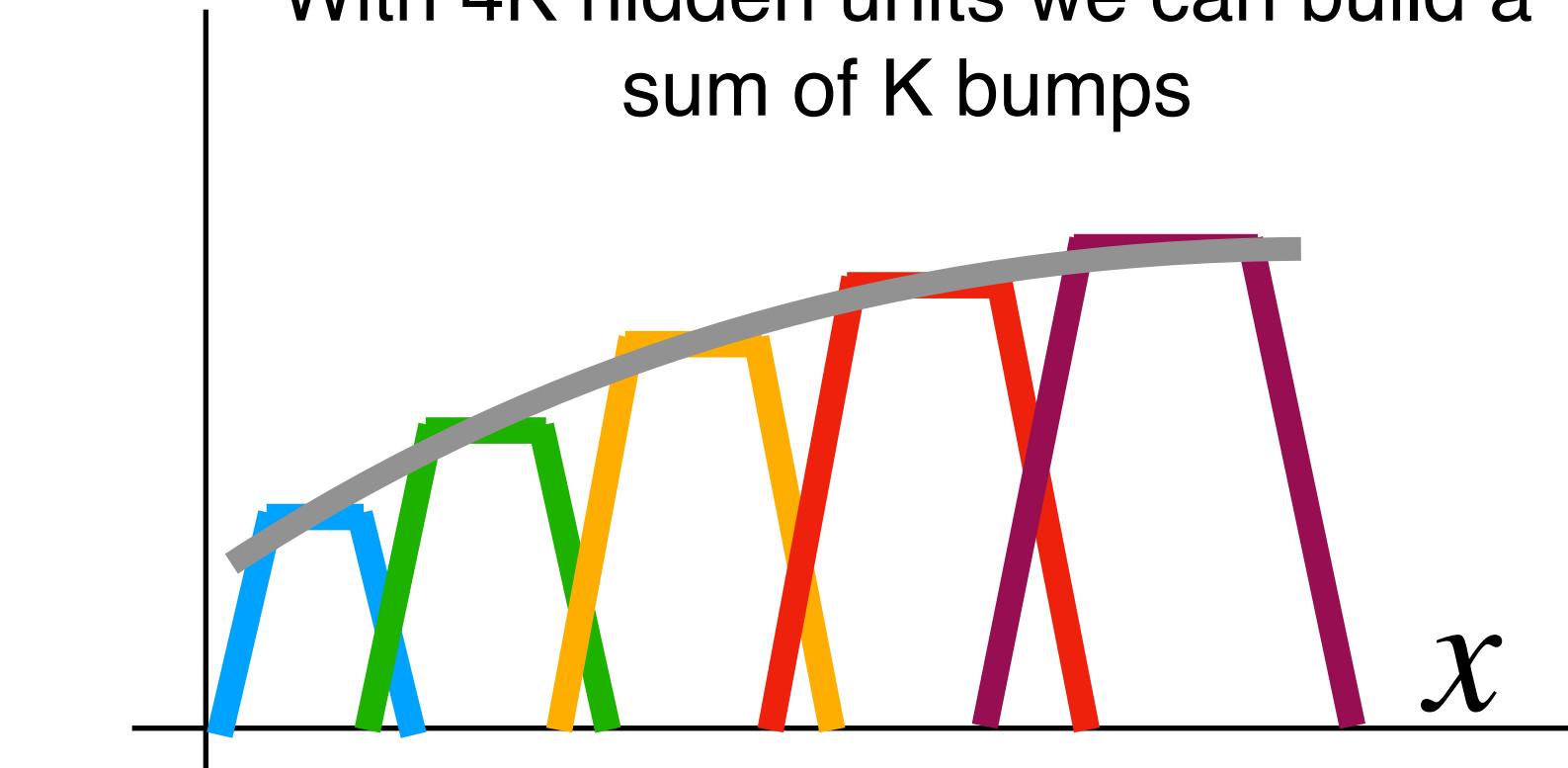
$$+ u_3 \max(0, w_3 x + b_3)$$

$$+ p$$

We can build a “bump function” using four hidden units

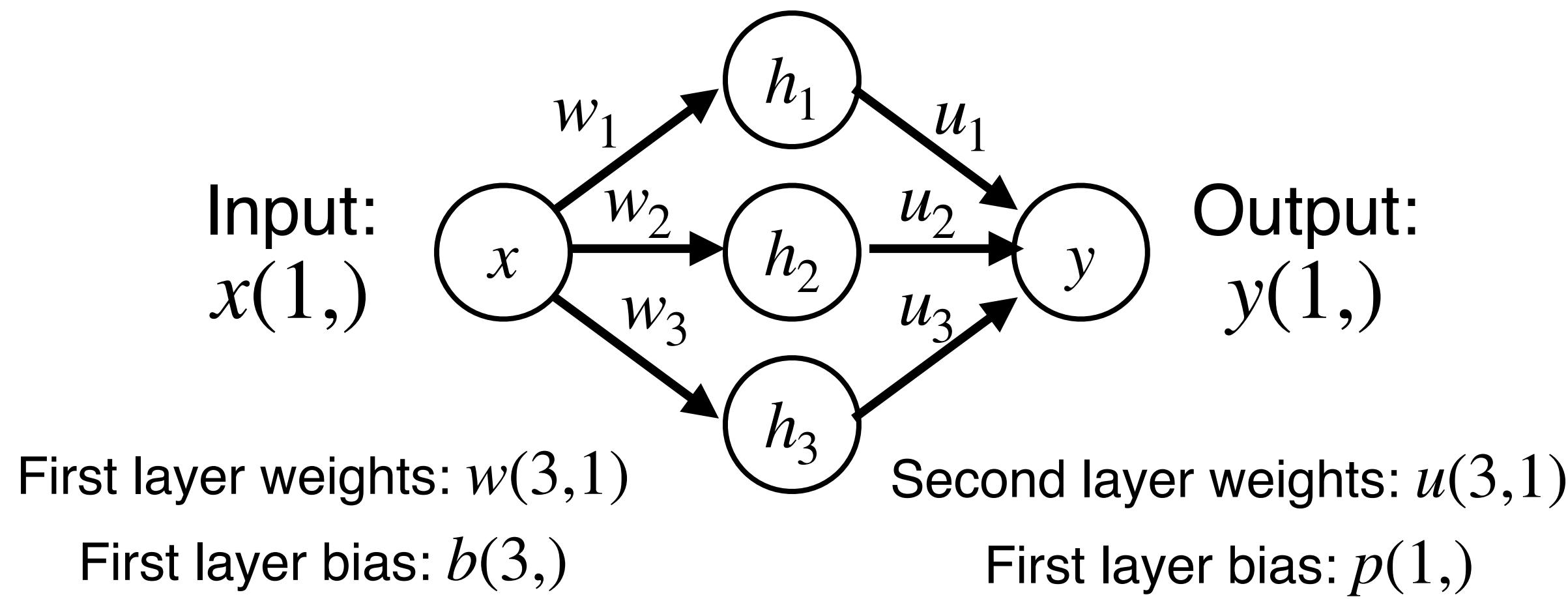


With 4K hidden units we can build a sum of K bumps



# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



$$h_1 = \max(0, w_1 x + b_1)$$

$$h_2 = \max(0, w_2 x + b_2)$$

$$h_3 = \max(0, w_3 x + b_3)$$

$$y = u_1 h_1 + u_2 h_2 + u_3 h_3 + p$$

$$y = u_1 \max(0, w_1 x + b_1)$$

$$+ u_2 \max(0, w_2 x + b_2)$$

$$+ u_3 \max(0, w_3 x + b_3)$$

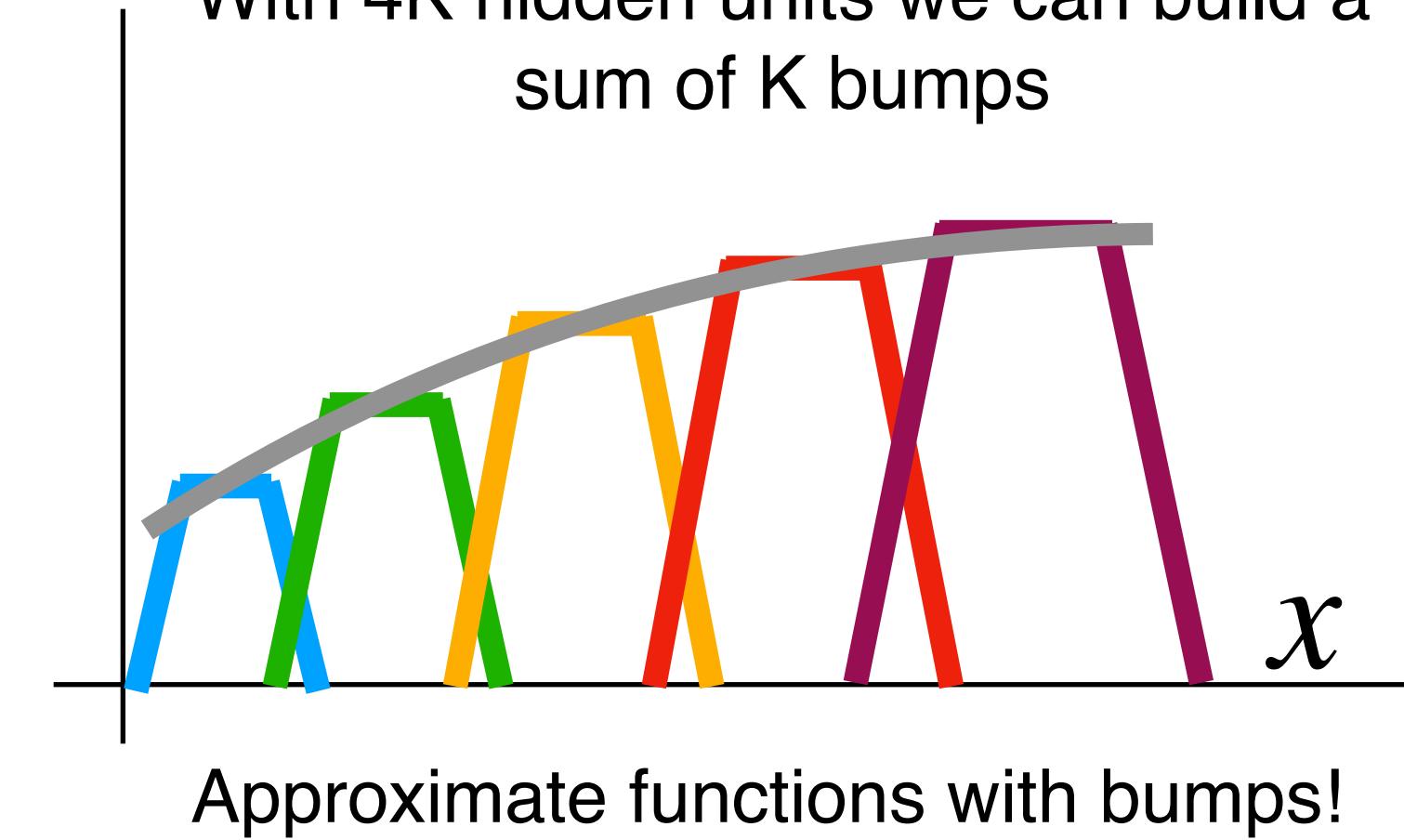
$$+ p$$

What about ...

- Gaps between bumps?
- Other nonlinearities?
- Higher-dimensional functions?

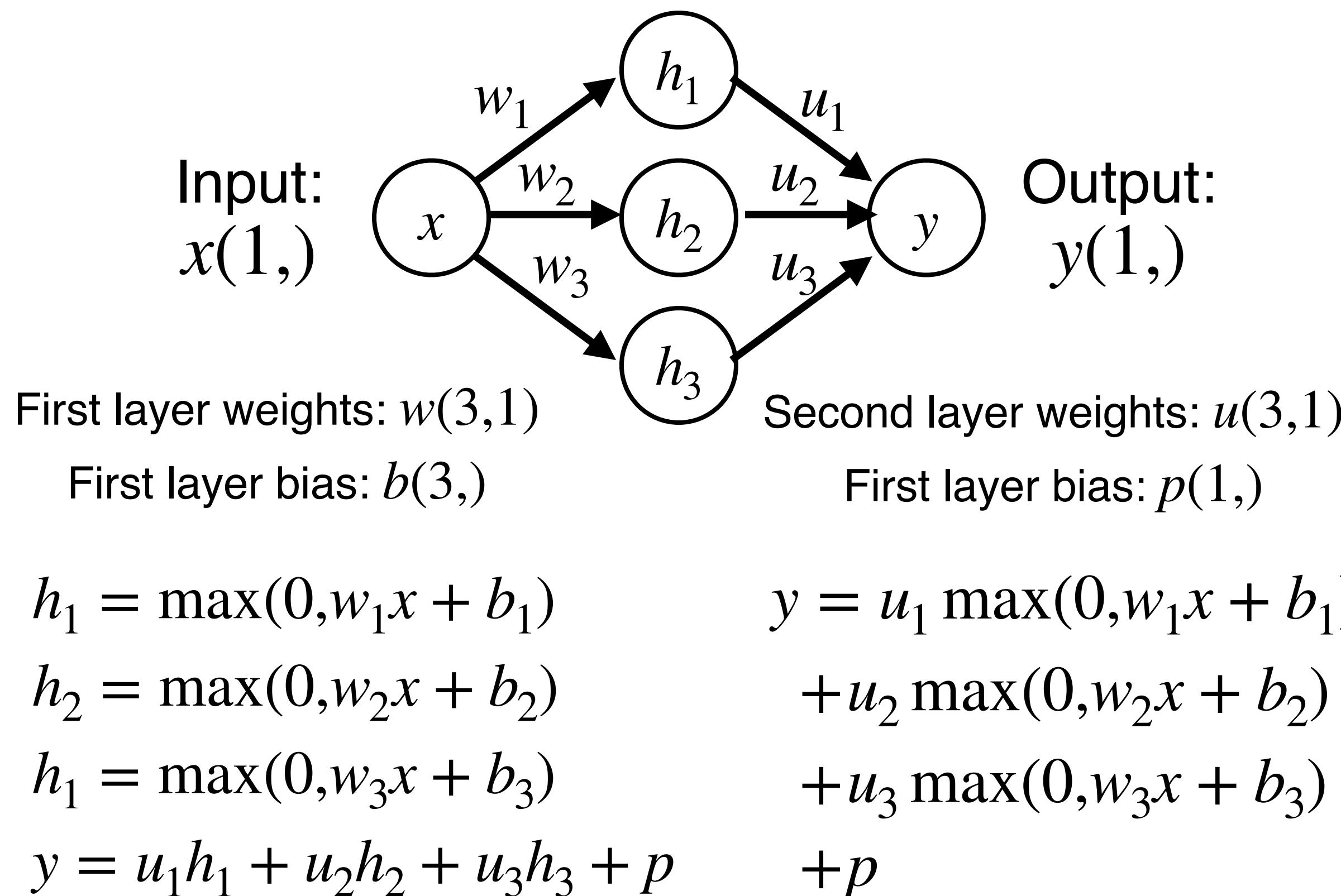
See [Nielsen, Chapter 4](#)

With 4K hidden units we can build a sum of K bumps

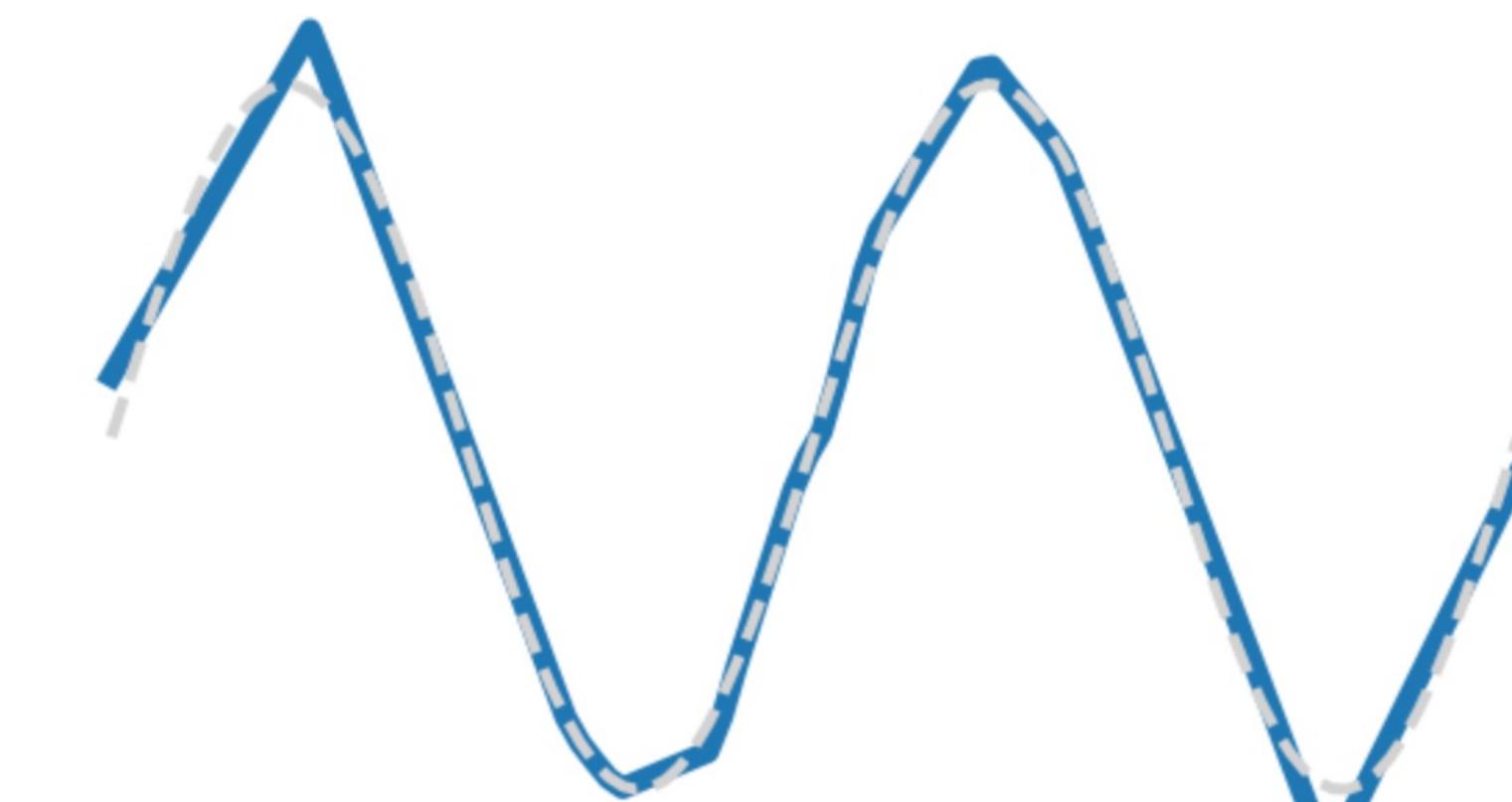


# Universal Approximation

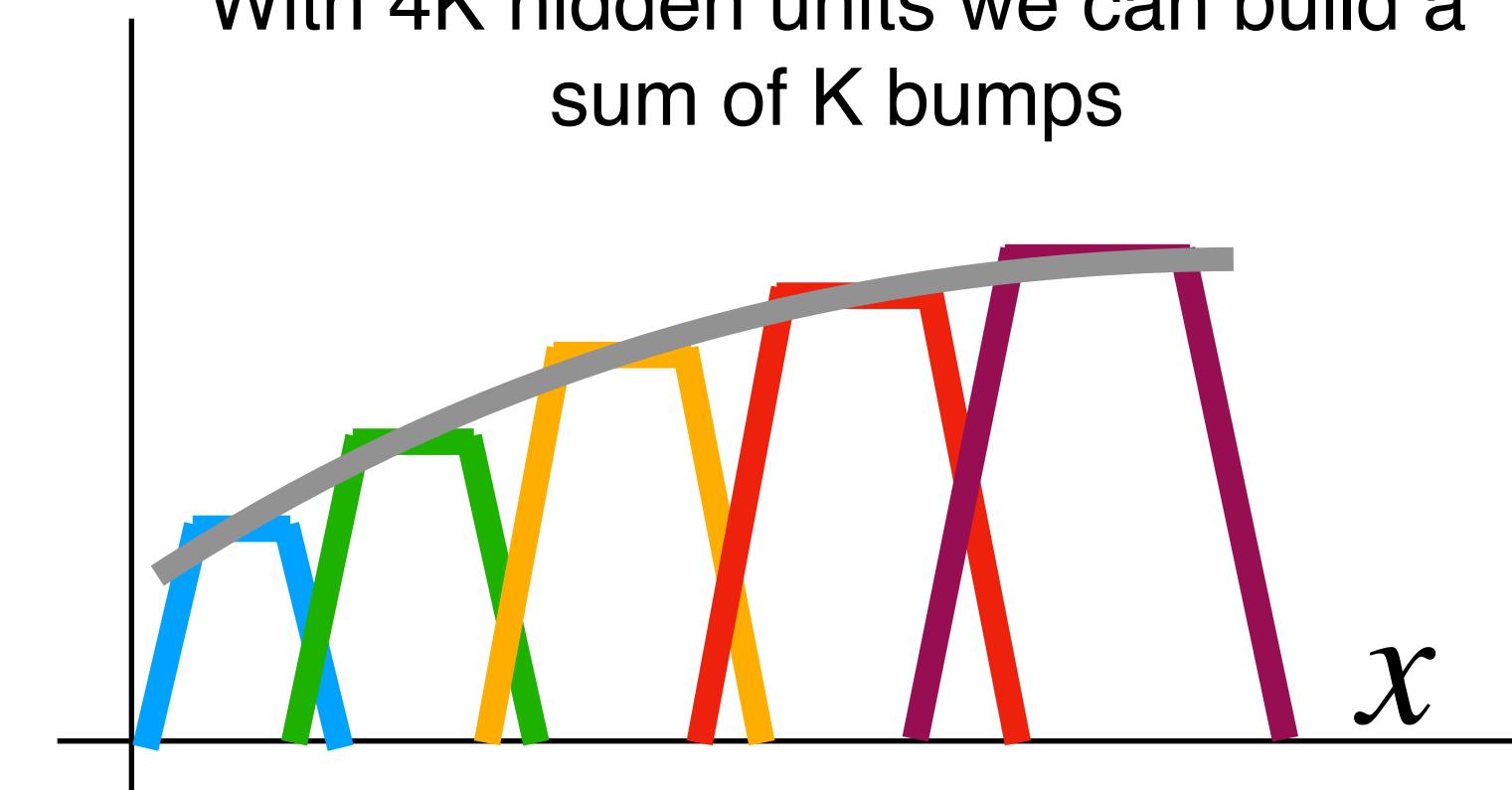
Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



Reality check: Networks don't really learn bumps!



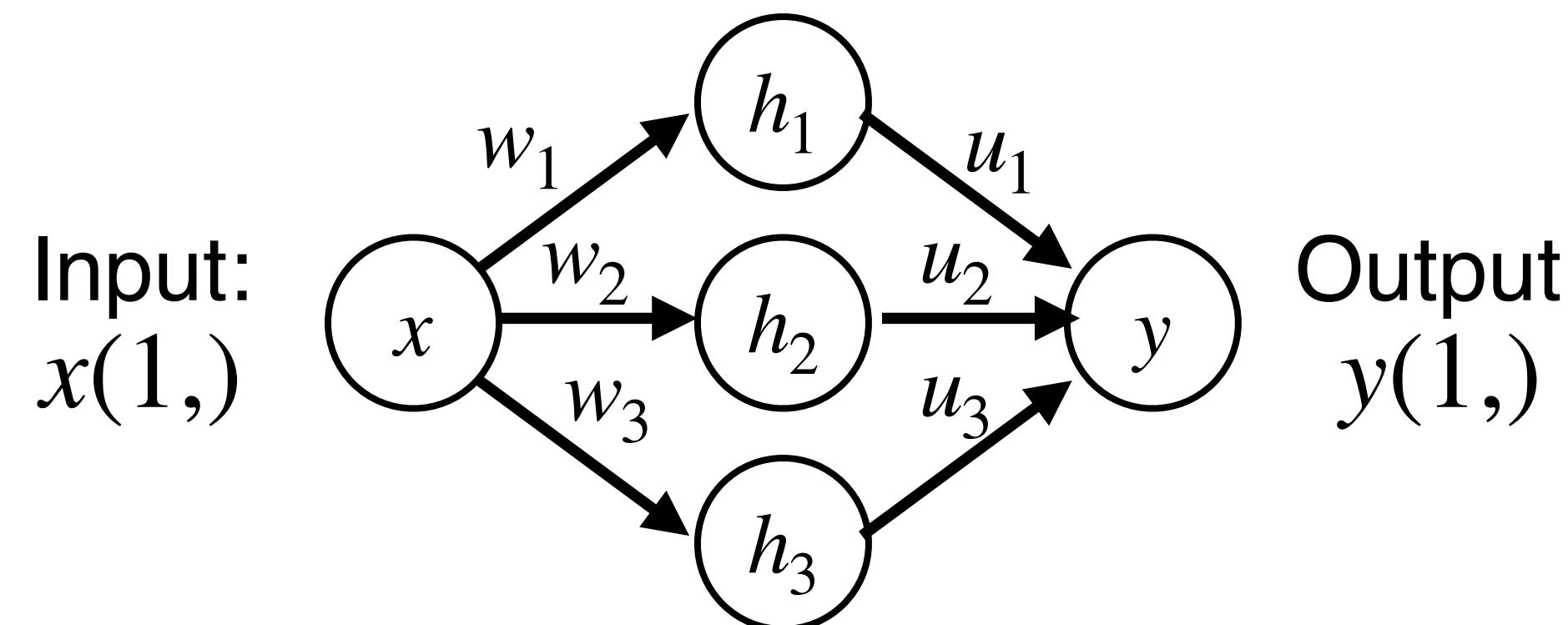
With 4K hidden units we can build a sum of K bumps



Approximate functions with bumps!

# Universal Approximation

Example: Approximating a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  with a two-layer ReLU network



Universal approximation tells us:

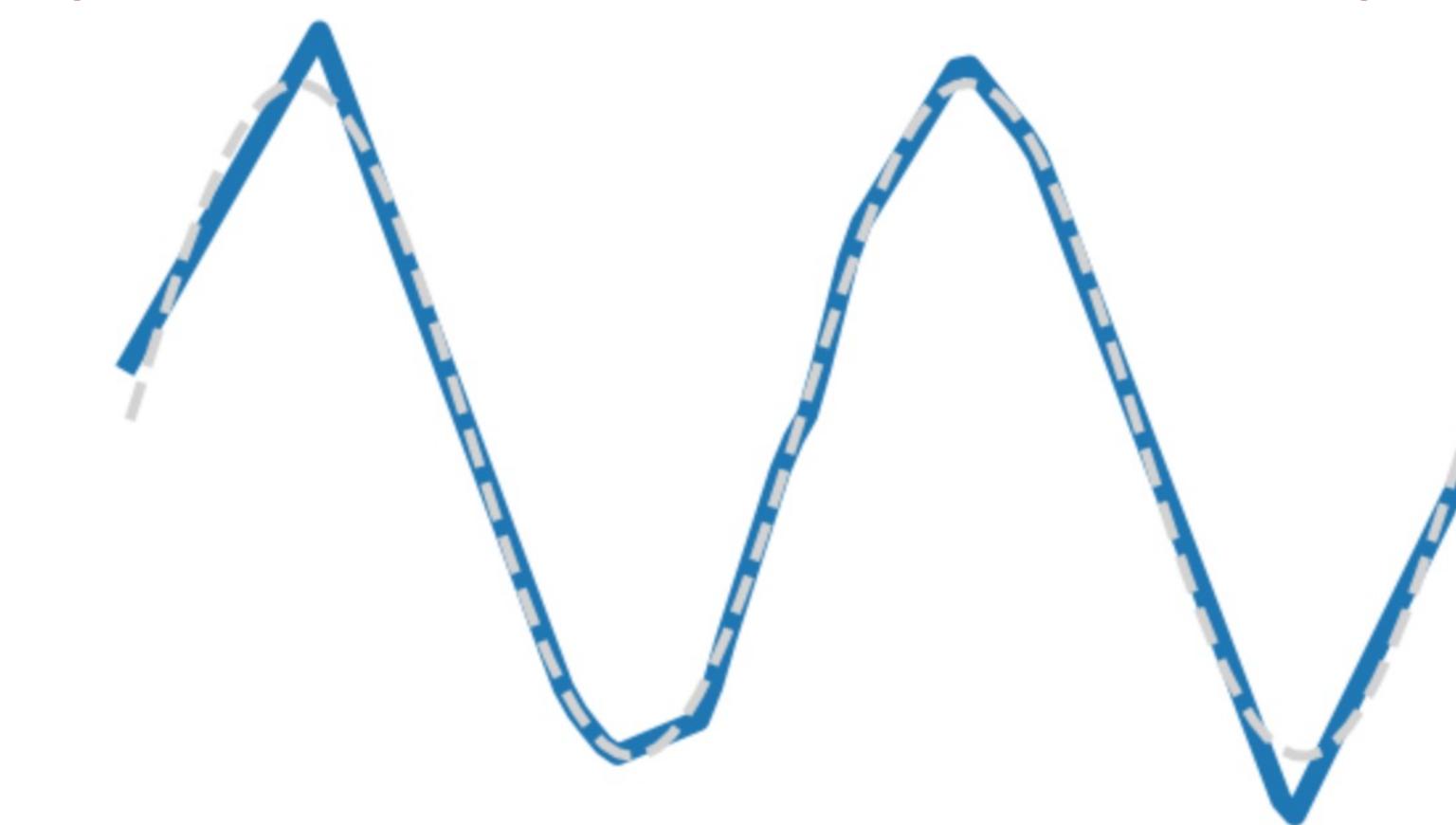
- Neural nets can represent any function

Universal approximation **DOES NOT** tell us:

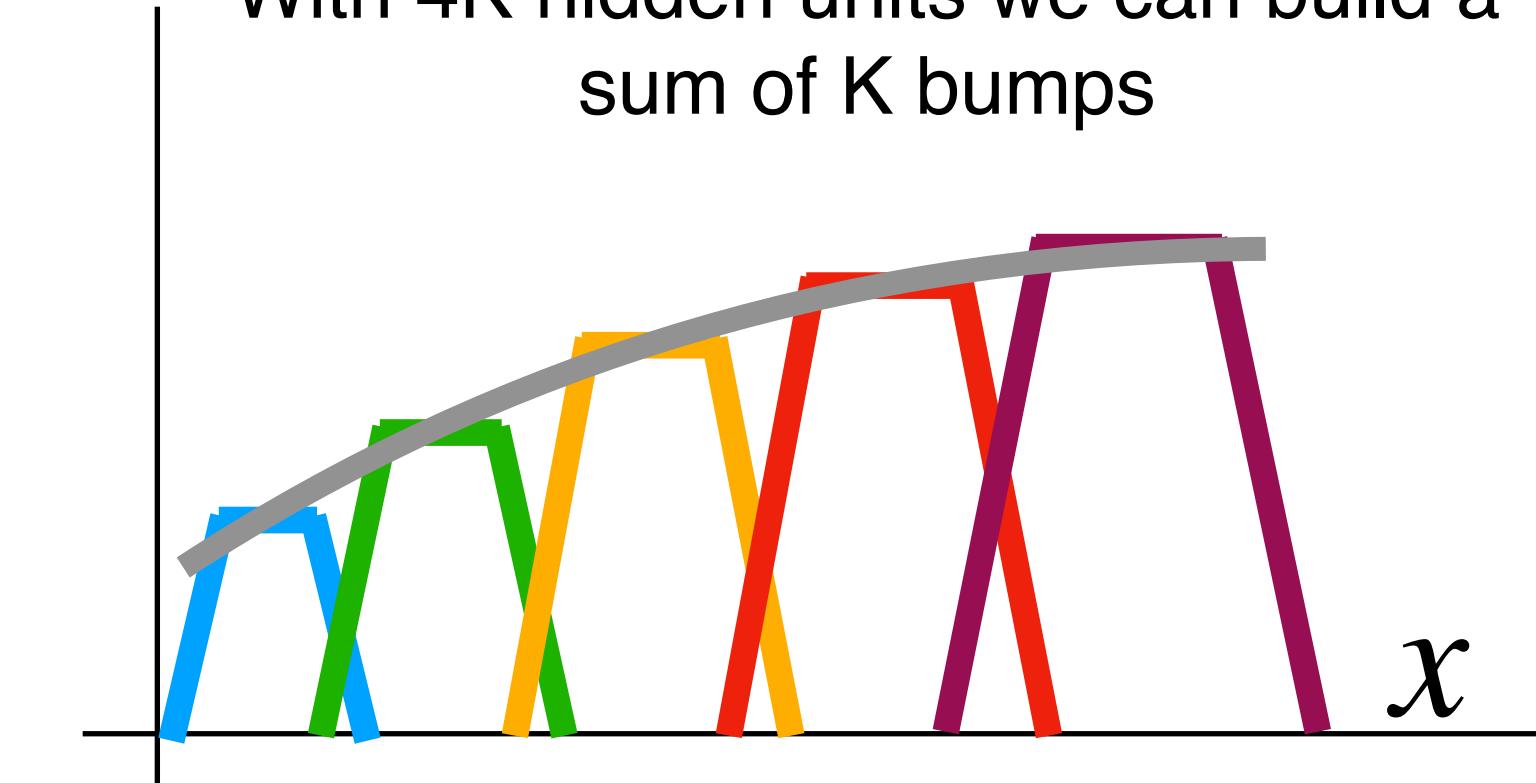
- Whether we can actually learn any function with SGD
- How much data we need to learn a function

Remember: kNN is also a universal approximator!

Reality check: Networks don't really learn bumps!



With 4K hidden units we can build a sum of K bumps



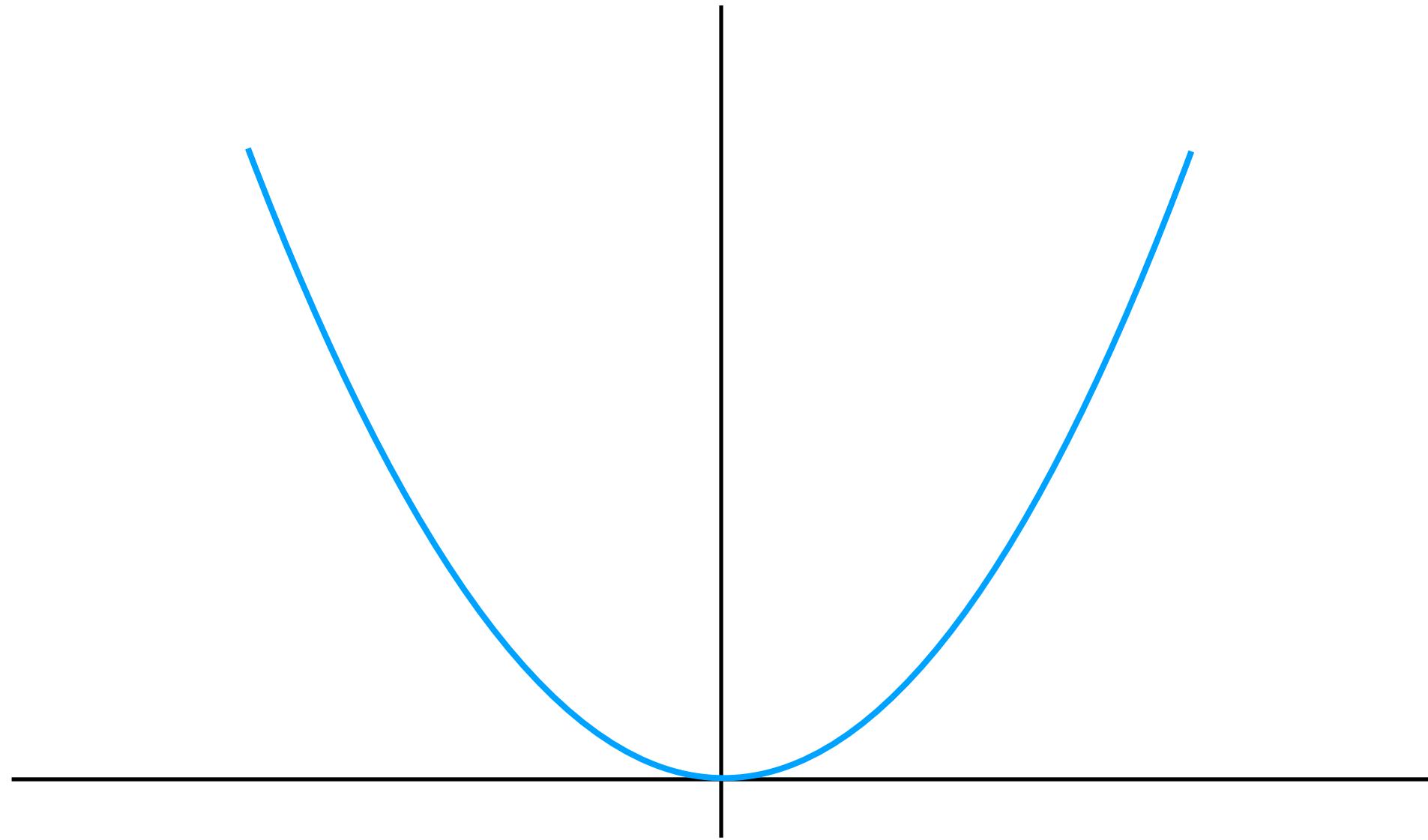
Approximate functions with bumps!

# Convex Functions

A function  $f: X \subseteq \mathbb{R}^N \rightarrow \mathbb{R}$  is **convex** if for all  $x_1, x_2 \in X, t \in [0,1]$ ,

$$f(tx_1 + (1 - t)x_2) \leq tf(x_1) + (1 - t)f(x_2)$$

Example:  $f(x) = x^2$  is convex:

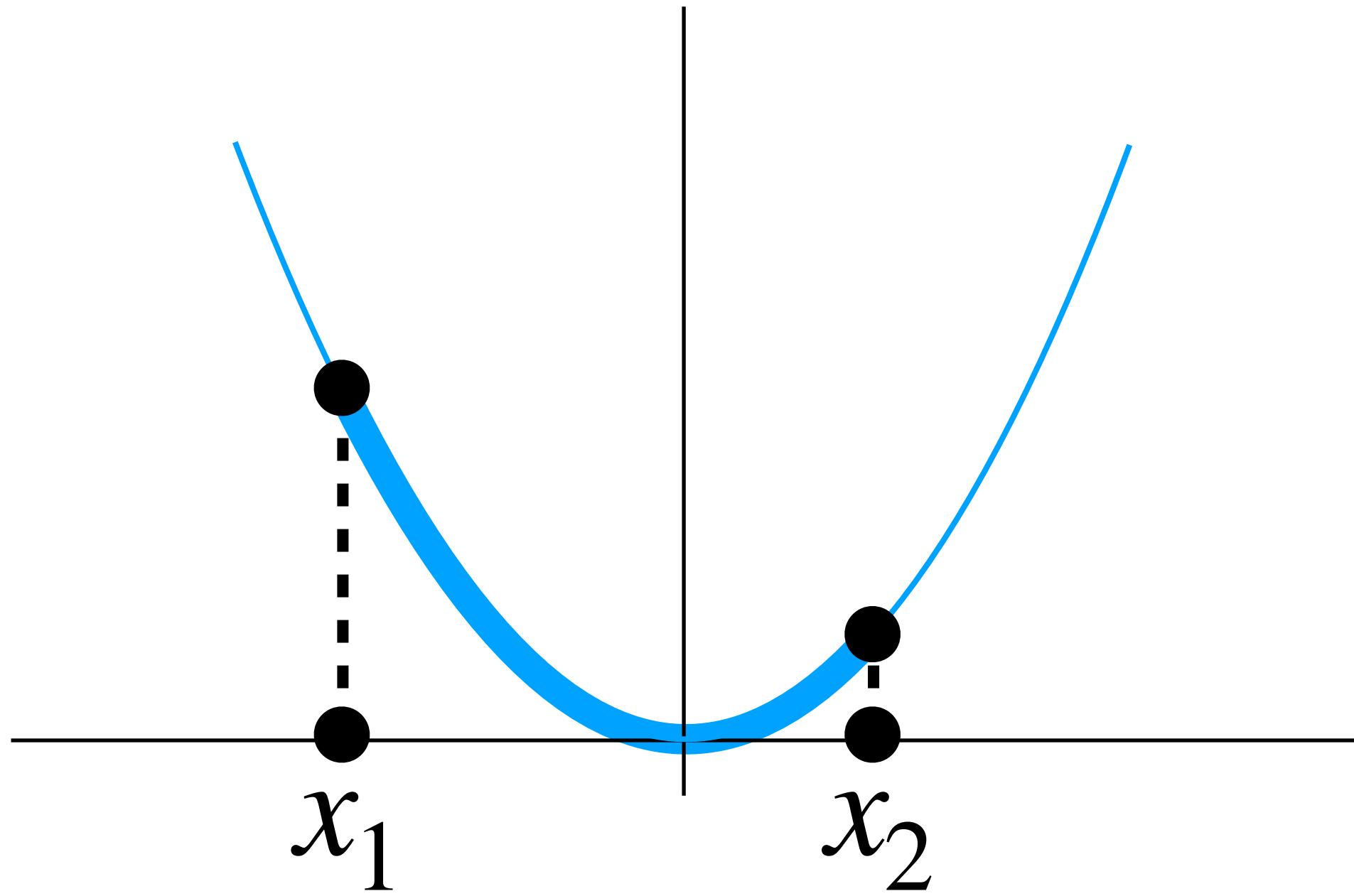


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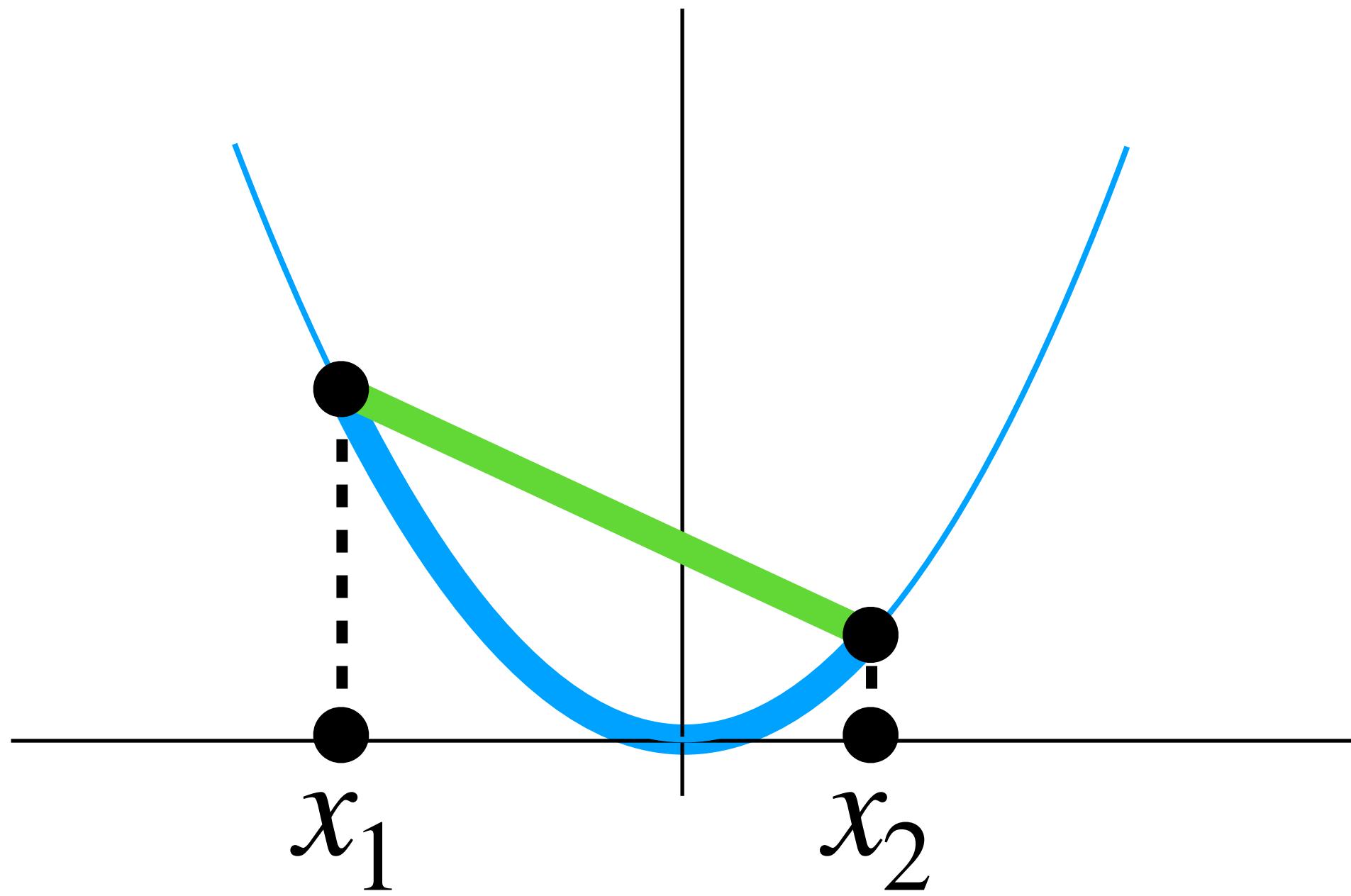


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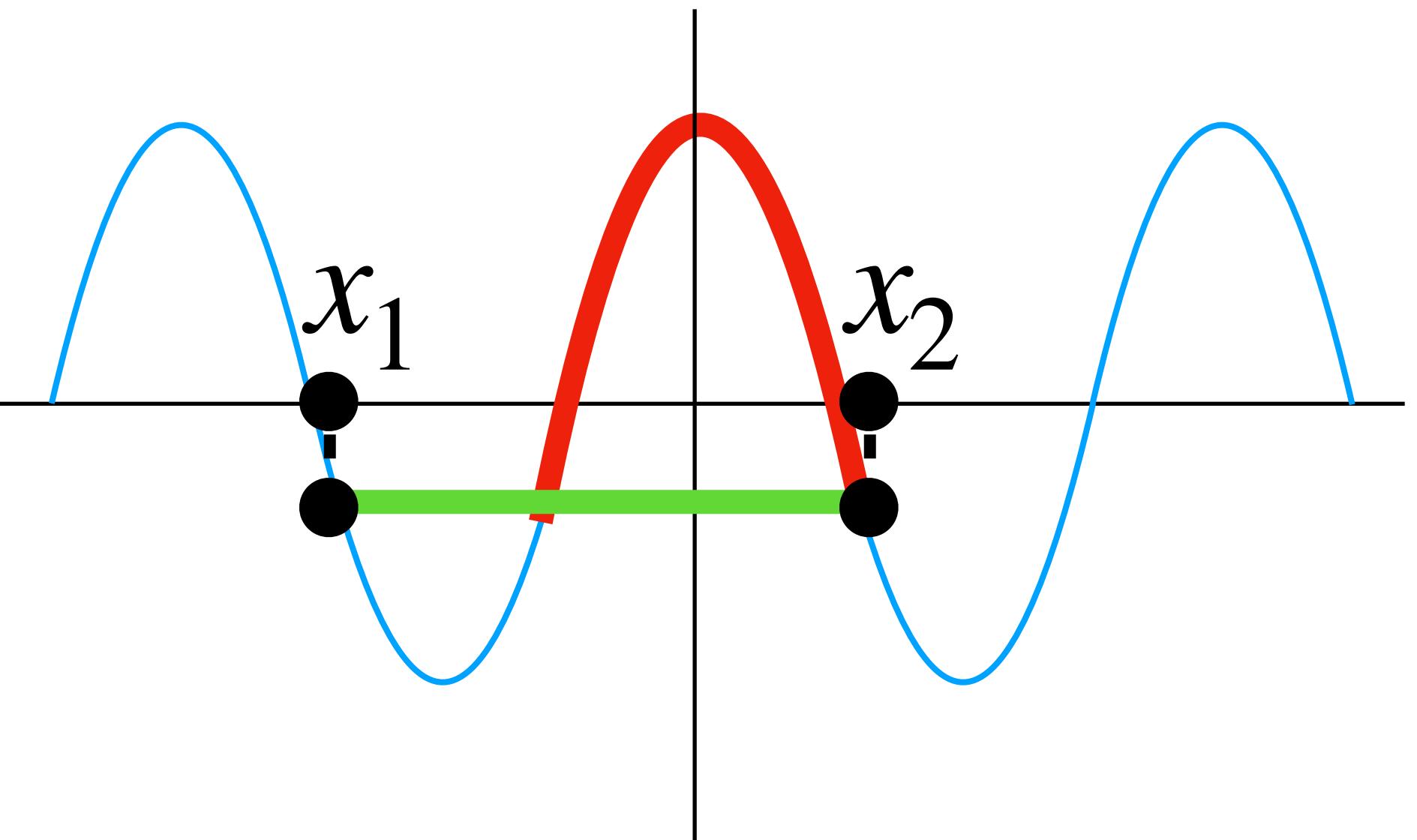


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Example:  $f(x) = \cos(x)$  is **not** convex:



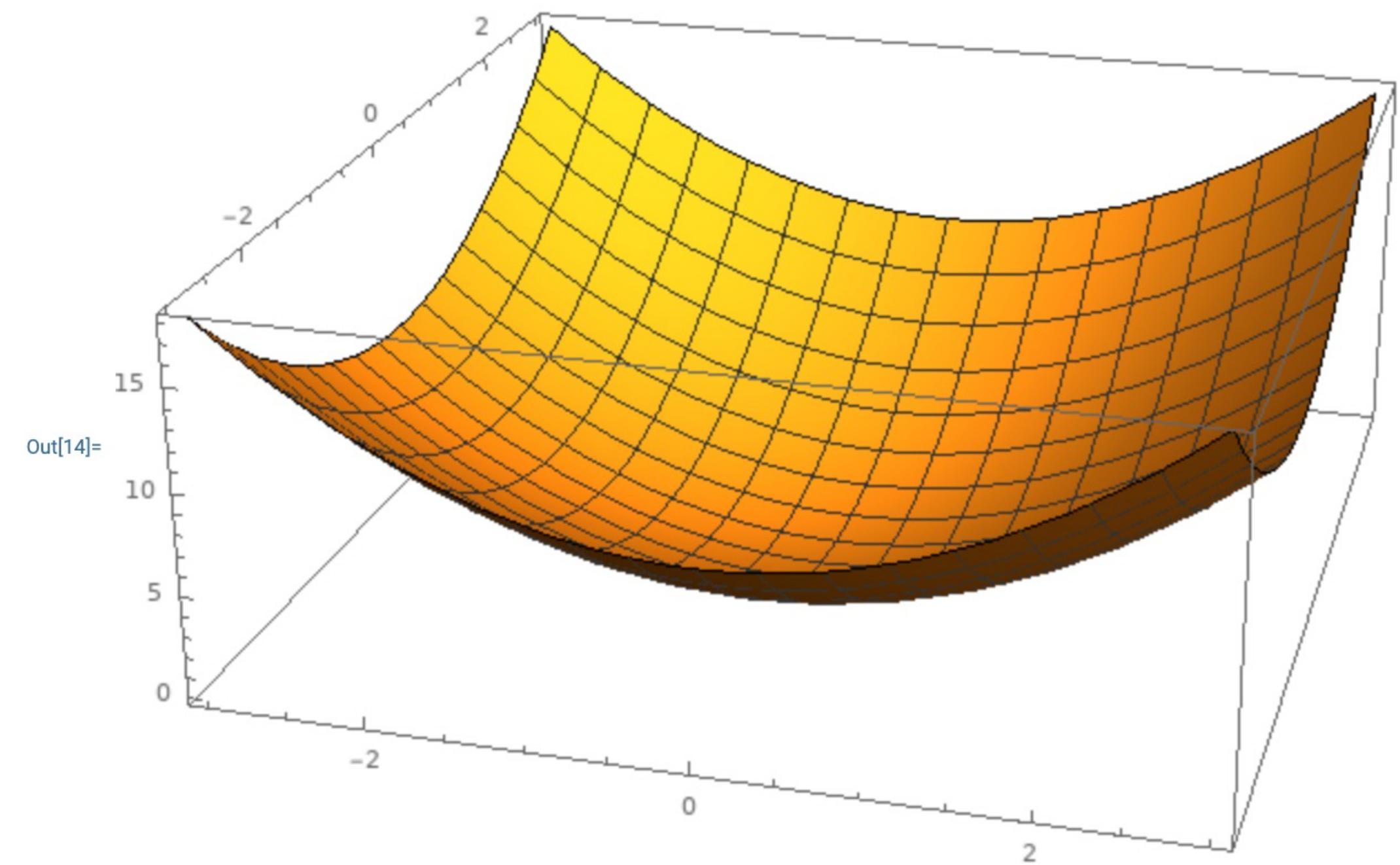
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**Intuition:** A convex function is a (multidimensional) bowl

Generally speaking, convex functions are **easy to optimize**: can derive theoretical guarantees about **converging to global minimum\***



# Convex Functions

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Linear classifiers optimize a **convex function!**

$$s = f(x; W) = Wx$$

$$L_i = -\log\left(\frac{e^{s_{y_i}}}{\sum_j e^{s_j}}\right) \quad \text{Softmax}$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1) \quad \text{SVM}$$

$$L = \frac{1}{N} \sum_{i=1}^N L_i + R(W) \quad \text{where } R(W) \text{ is L2 or L1 regularization}$$



# Convex Functions

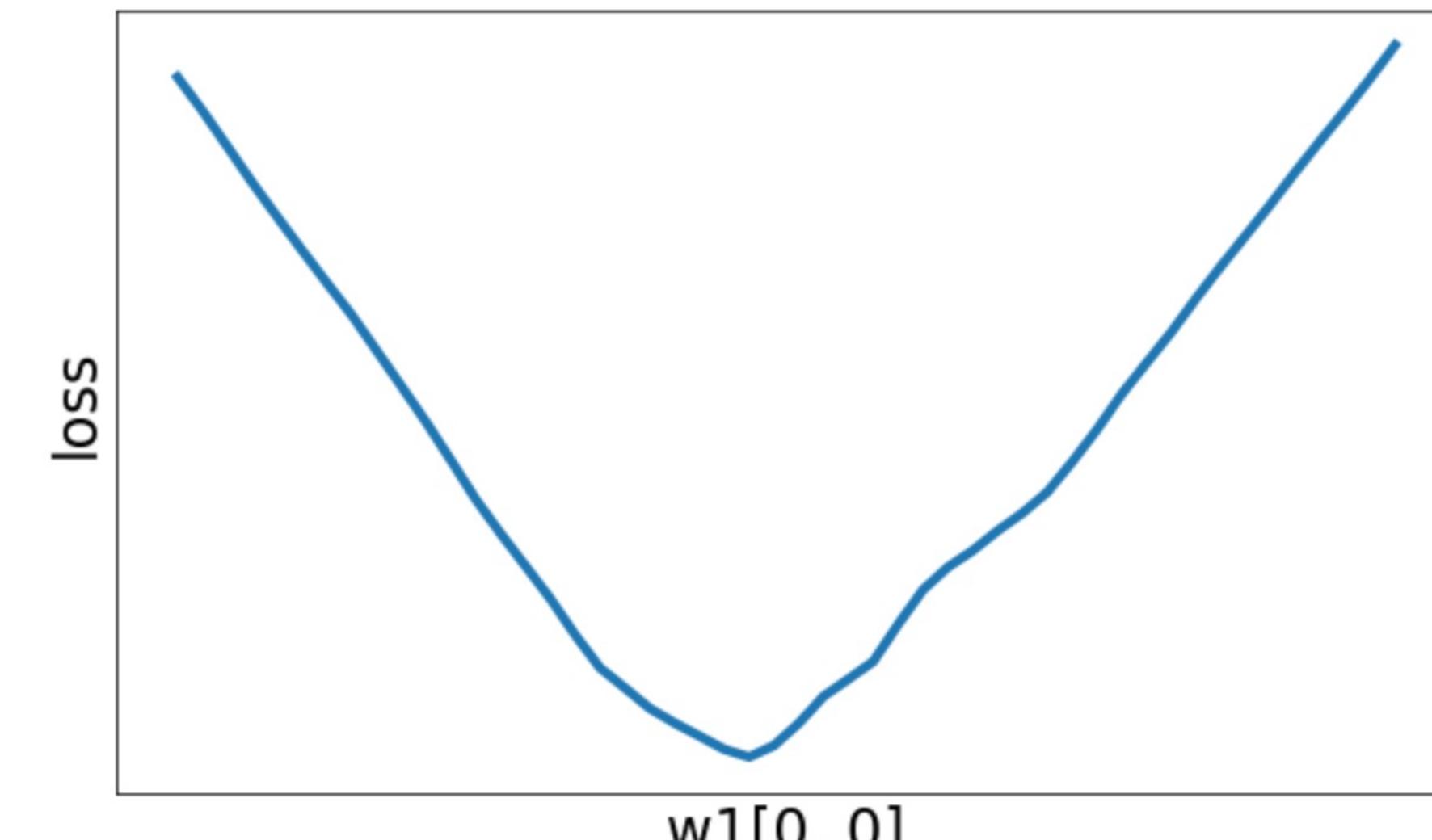
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Neural net losses sometimes look convex-ish:



1D slice of loss landscape for a 4-layer ReLU network with 10 input features, 32 units per hidden layer, 10 categories, with softmax loss

# Convex Functions

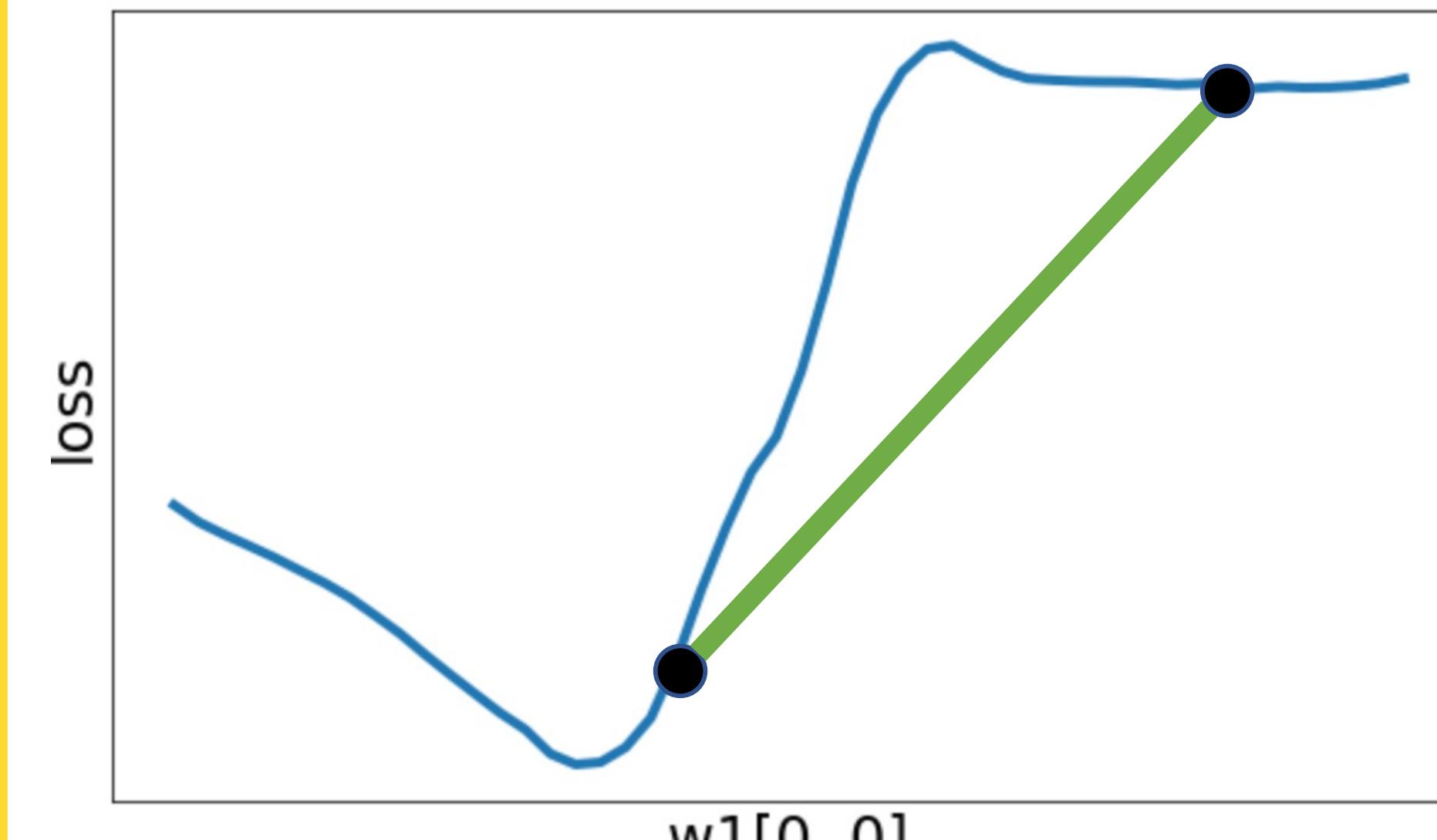
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Generally speaking, convex functions are **easy to optimize**: can derive theoretical guarantees about **converging to global minimum\***

But often clearly nonconvex:



1D slice of loss landscape for a 4-layer ReLU network with 10 input features, 32 units per hidden layer, 10 categories, with softmax loss

# Convex Functions

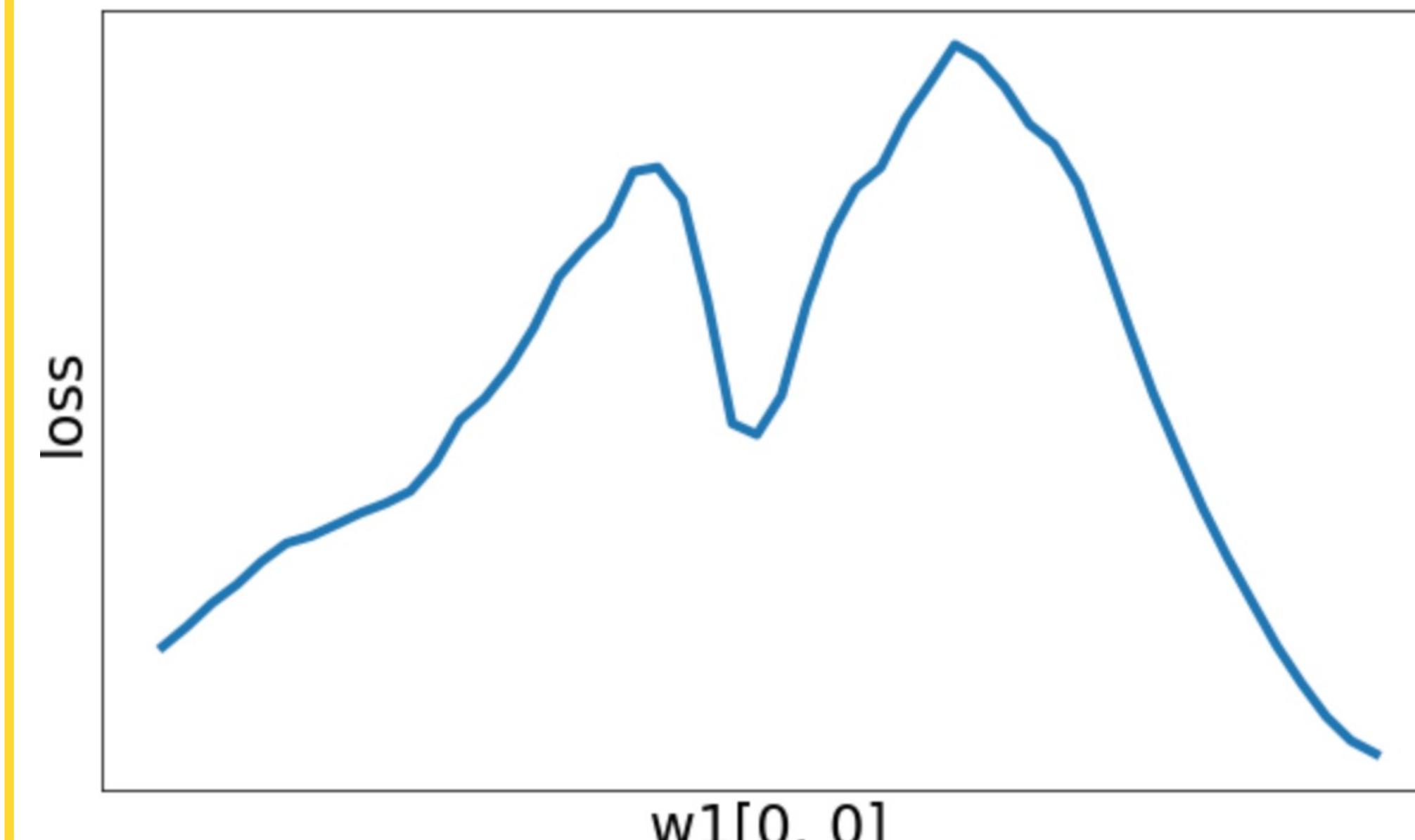
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**Intuition:** A convex function is a (multidimensional) bowl

Generally speaking, convex functions are **easy to optimize**: can derive theoretical guarantees about **converging to global minimum\***

With local minima:



1D slice of loss landscape for a 4-layer ReLU network with 10 input features, 32 units per hidden layer, 10 categories, with softmax loss

# Convex Functions

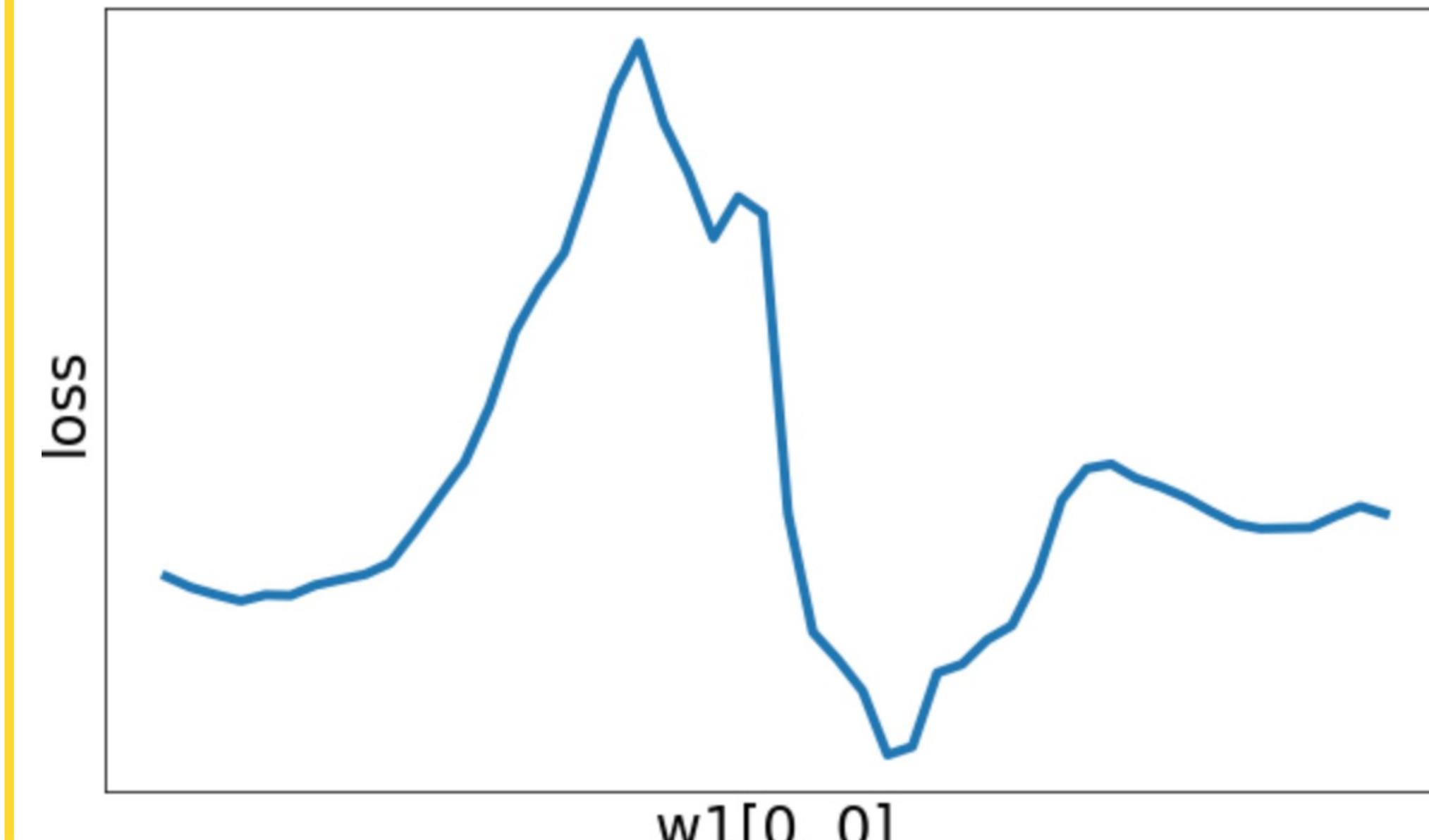
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Generally speaking, convex functions are **easy to optimize**: can derive theoretical guarantees about **converging to global minimum\***

Can get very wild!



1D slice of loss landscape for a 4-layer ReLU network with 10 input features, 32 units per hidden layer, 10 categories, with softmax loss

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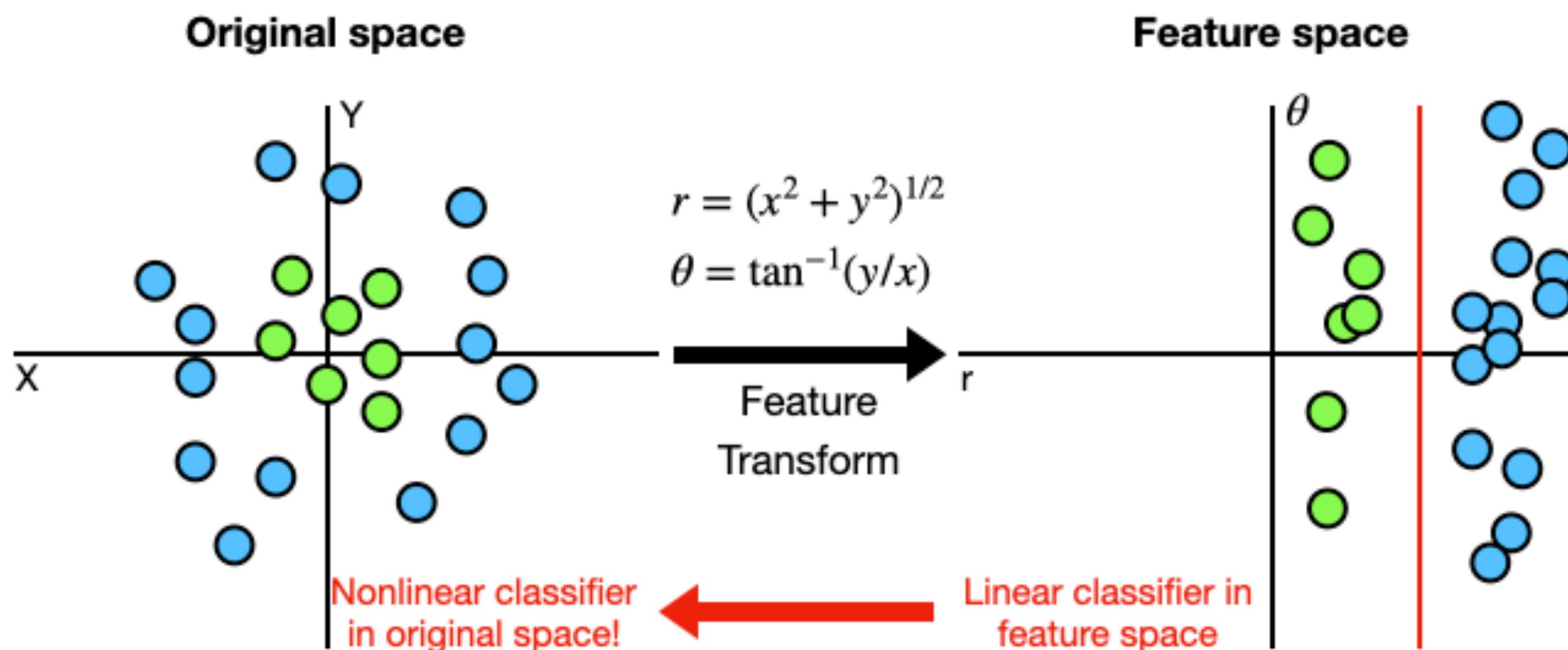
Most neural networks need **nonconvex optimization**

- Few or no guarantees about convergence
- Empirically it seems to work anyway
- Active area of research

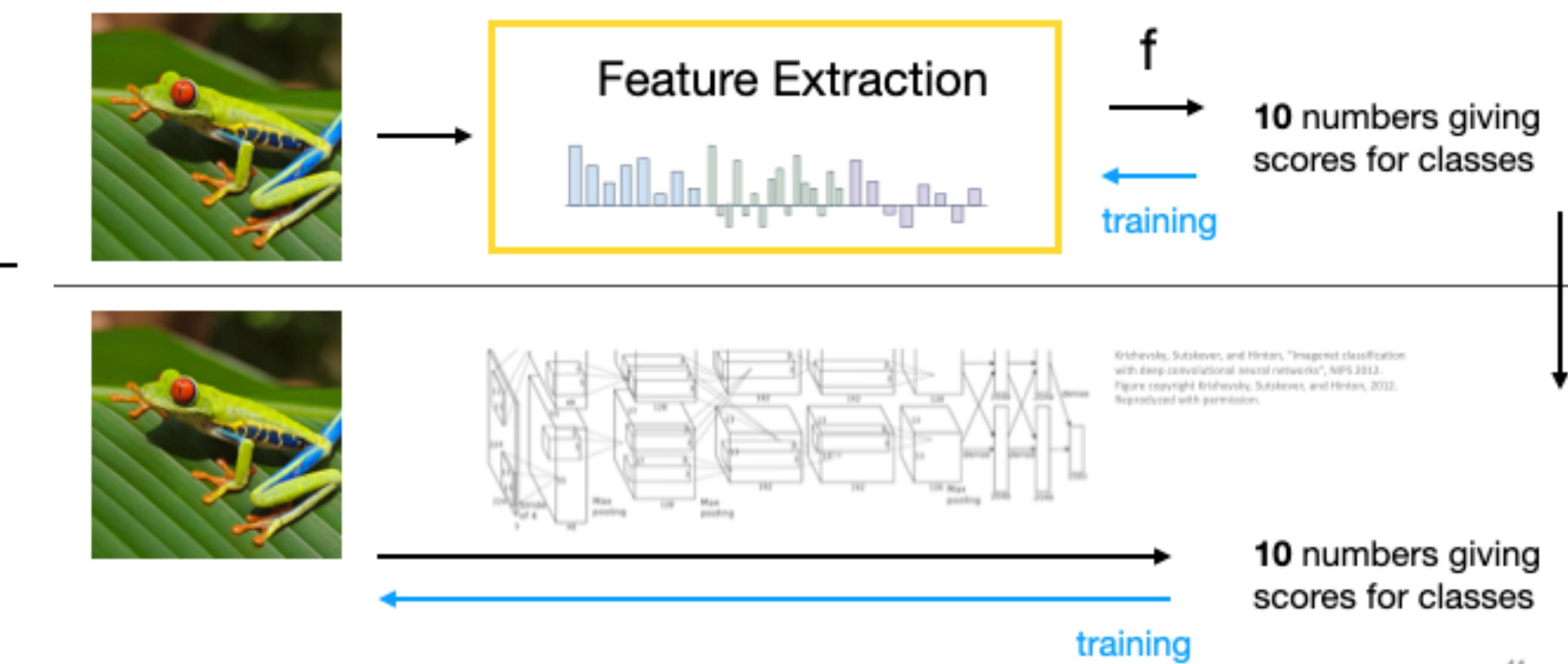


# Summary

Feature transform + Linear classifier allows nonlinear decision boundaries



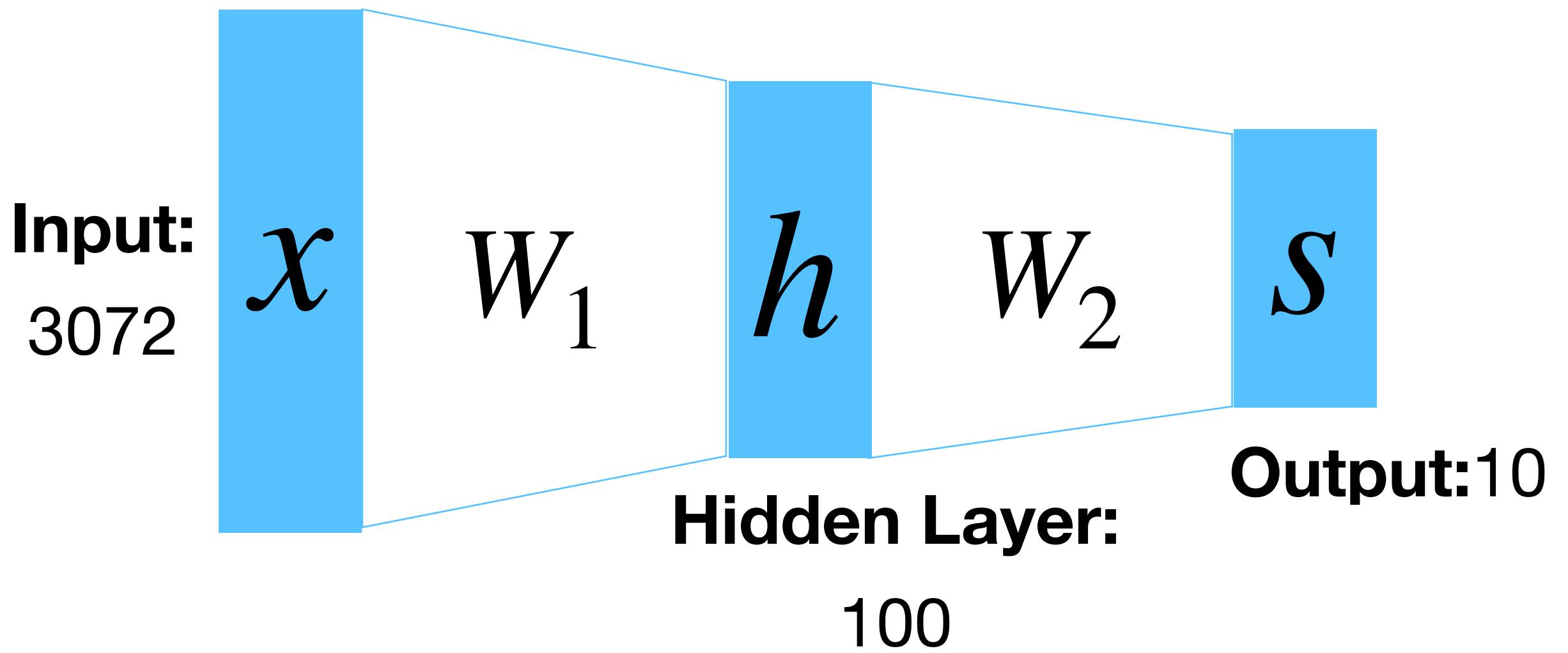
Neural Networks as learnable feature transforms



# Summary

From linear classifiers to  
fully-connected networks

$$f(x) = W_2 \max(0, W_1 x + b_1) + b_2$$



Linear classifier: One template per class



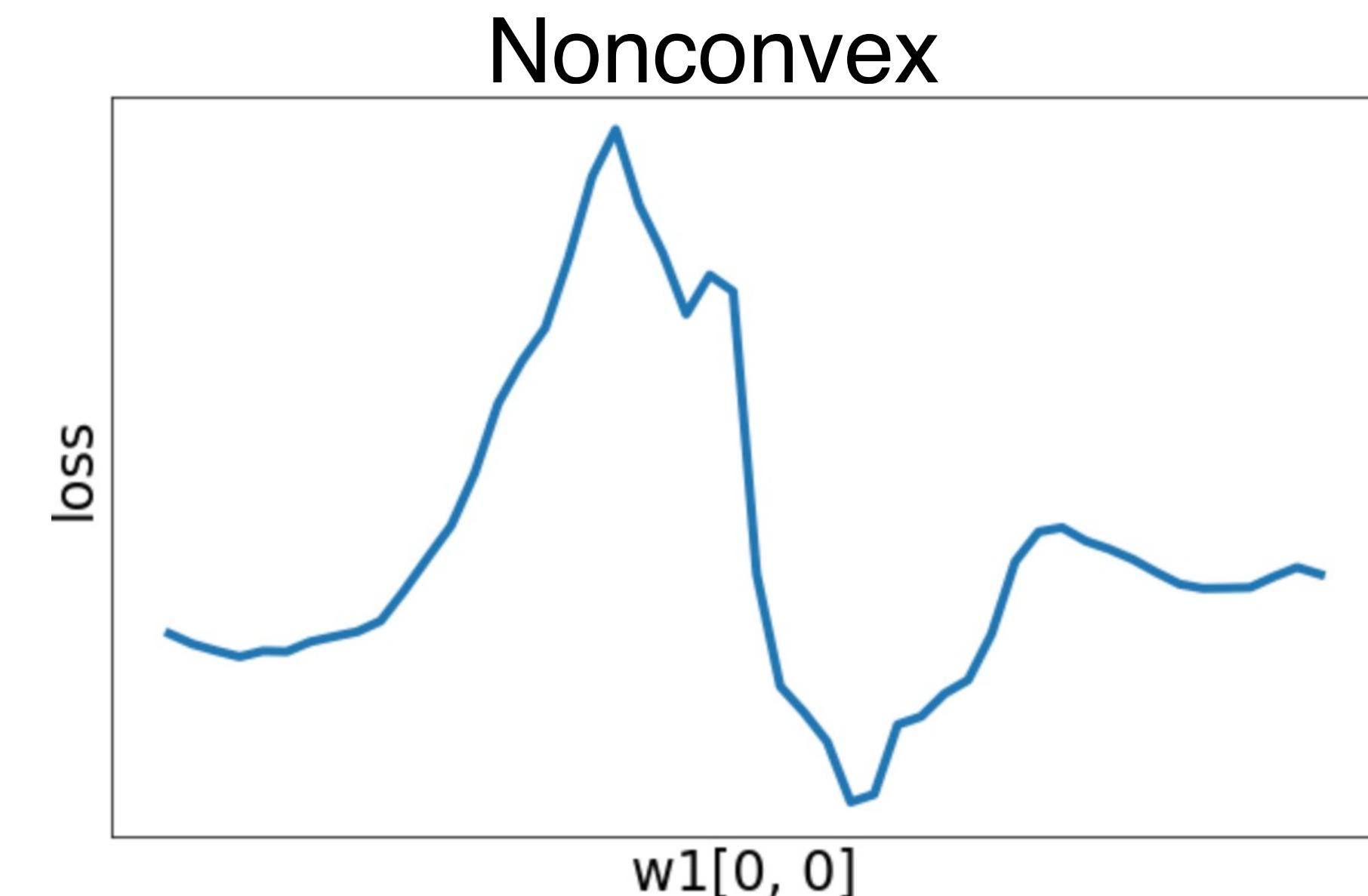
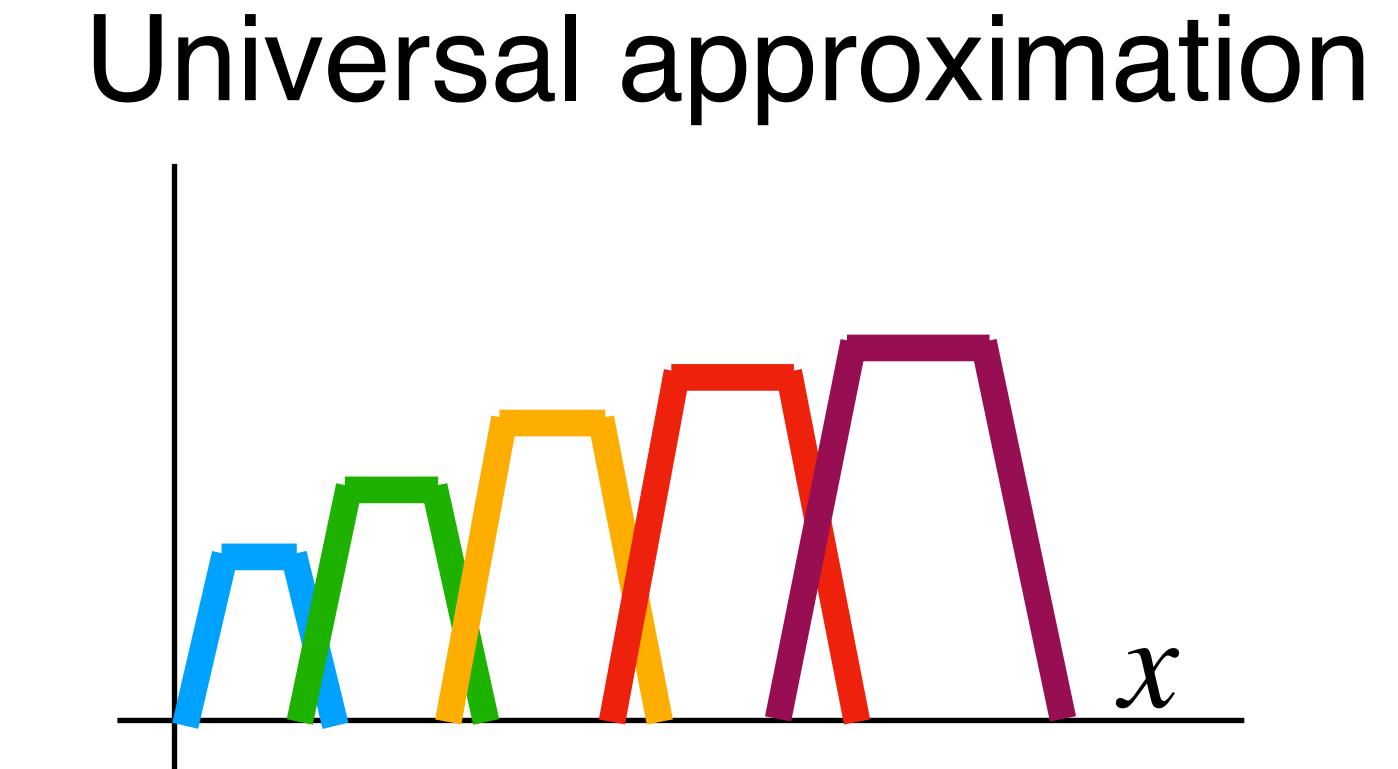
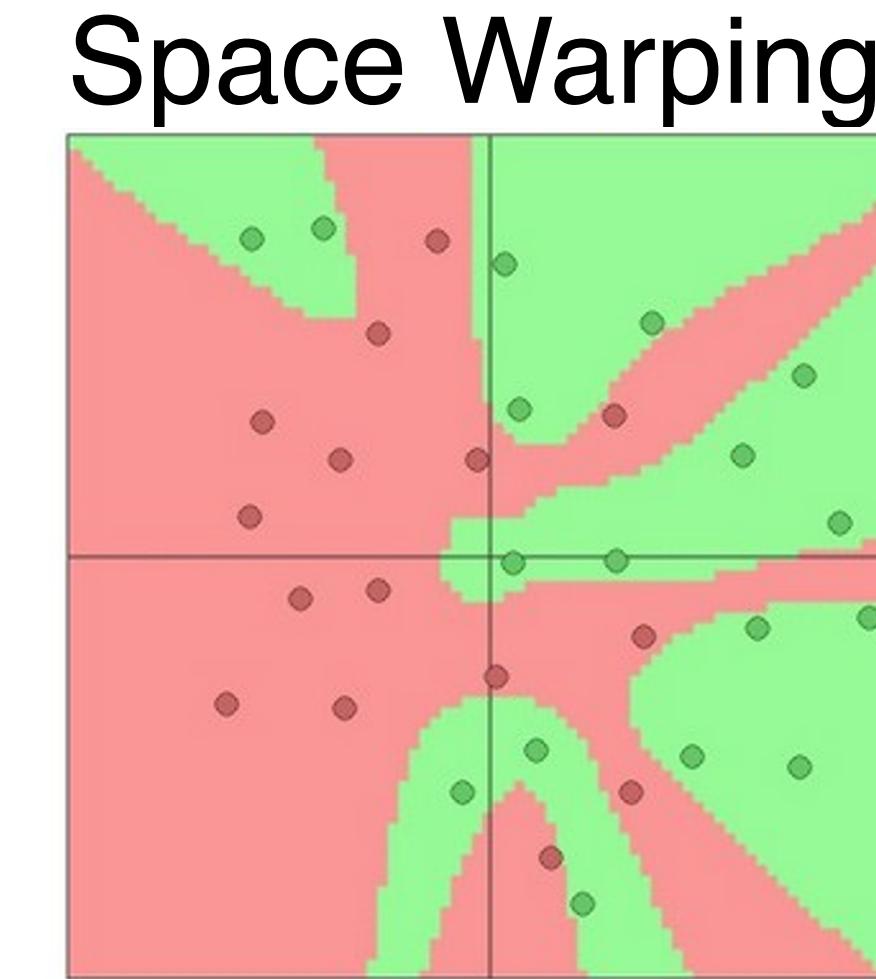
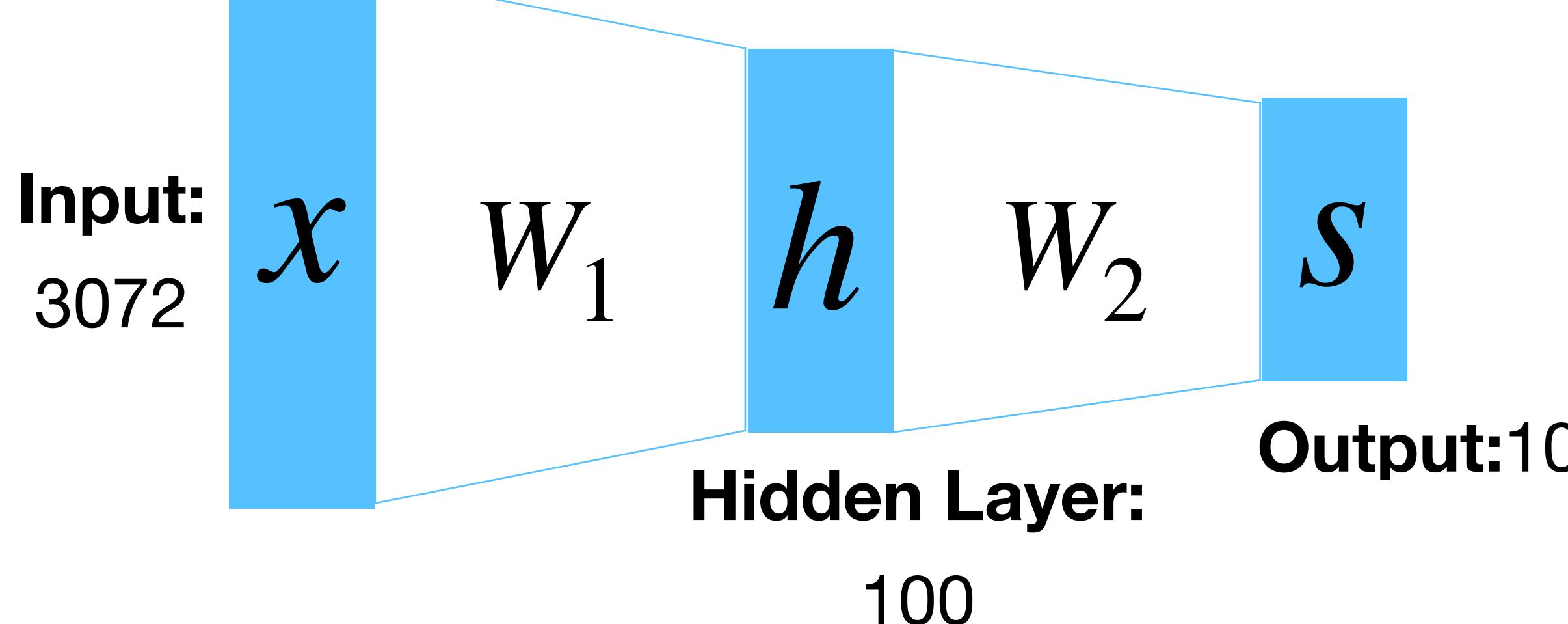
Neural networks: Many reusable templates



# Summary

From linear classifiers to  
fully-connected networks

$$f(x) = W_2 \max(0, W_1 x + b_1) + b_2$$



# Problem: How to compute gradients?

---

$$s = W_2 \max(0, W_1 x + b_1) + b_2$$

Nonlinear score function

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

Per-element data loss

$$R(W) = \sum_k W_k^2$$

L2 regularization

$$L(W_1, W_2, b_1, b_2) = \frac{1}{N} \sum_{i=1}^N L_i + \lambda R(W_1) + \lambda R(W_2) \text{ Total loss}$$

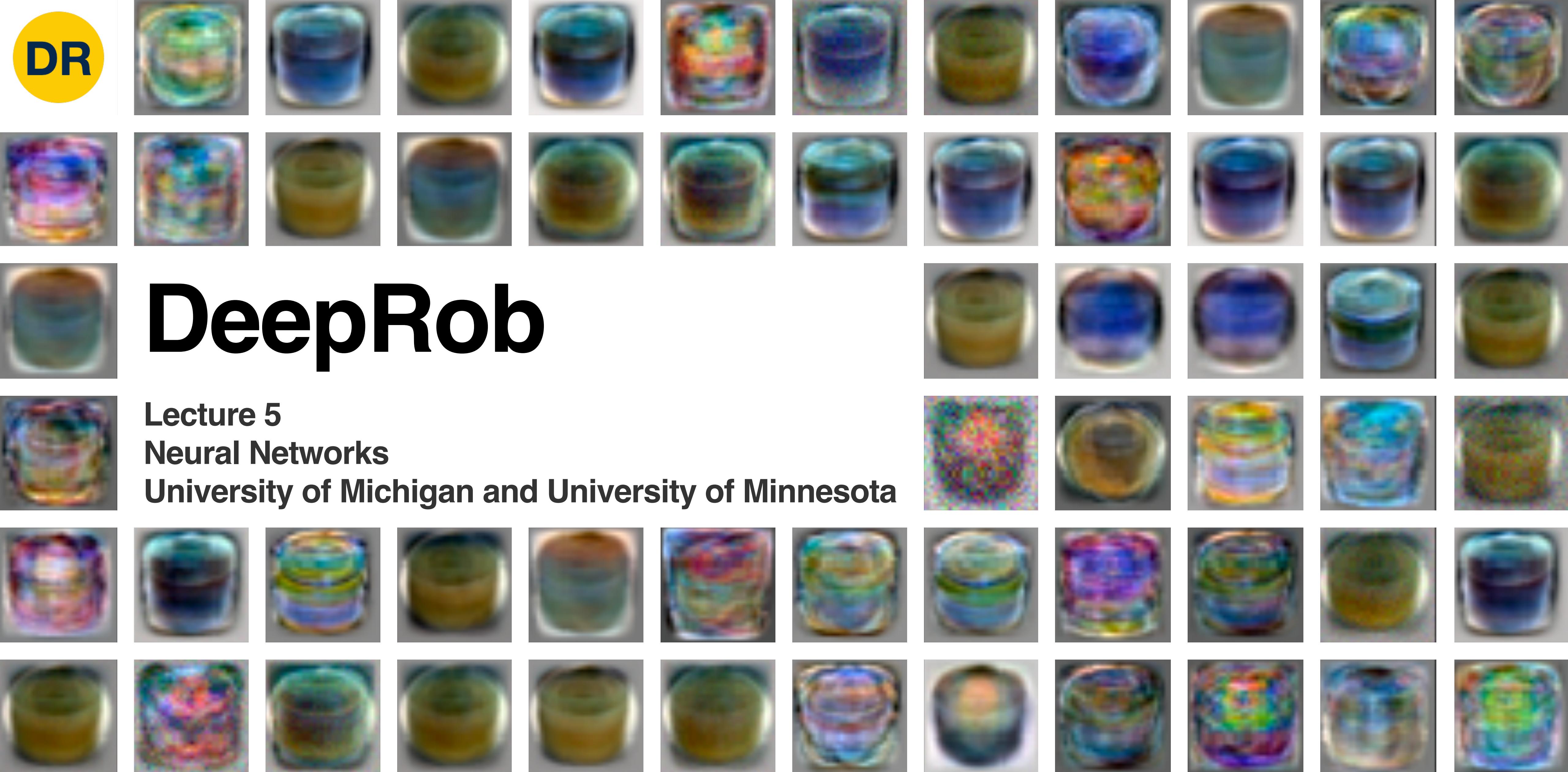
If we can compute  $\frac{\delta L}{\delta W_1}, \frac{\delta L}{\delta W_2}, \frac{\delta L}{\delta b_1}, \frac{\delta L}{\delta b_2}$  then we can optimize with SGD



# Next time: Backpropagation



**DR**



# DeepRob

**Lecture 5**  
**Neural Networks**  
**University of Michigan and University of Minnesota**

